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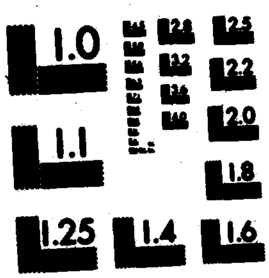

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Improvement of Combat Performance for Existing and Future Aircraft

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.409

IMPROVEMENT OF COMBAT PERFORMANCE FOR EXISTING AND FUTURE AIRCRAFT

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Papers presented at the Flight Mechanics Panel Symposium held in ~~Istrana AFB~~, Treviso, Italy
from 14 to 17 April 1986.

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— Improving the co-operation among member nations in aerospace research and development;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;

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PREFACE

In planning the enhancement of a defence capability to meet a growing threat within increasing financial constraints, it is invariably necessary, and is current practice in all NATO countries, to consider varying options for improvement of existing weapon systems as an alternative to embarking on totally new systems concepts. A wide range of technical options are now available to improve the overall performance of a weapon system. Many of these features are equally applicable for embodiment in new designs or in existing combat aircraft. In considering these varied options, cost and effectiveness remain the common constraints.

The intention of this AGARD multi-panel symposium was to present the audience with examples of typical requirements for these types of programmes and to give overviews of the most relevant technical disciplines, showing the highlights of the most promising future trends and to comment on examples of realised or planned programmes. Though the technical scope of the symposium was very broad with active contribution from six AGARD Panels (FMP, FDP, SMP, PEP, GCP, AVP), clear statements and trends were projected in the individual presentations, discussions and in the final Round Table summary.

The following observations summarise the actual situation and future trends.

Requirements:

Design requirements are heavily dependent on the individual mission profile. The Deep Penetration mission requires high thrust levels, low radar cross-sections, sophisticated ECM-equipment and "smart" stand-off weapons. Close Air Support needs high flexibility according to changing special scenarios. Air-to-Air requires early target recognition, Beyond Visual Range fighting capability, high climb rates and maximum speed, and also high agility if close-in combat is to be considered. A reduction of life-cycle cost is always a prime requirement and should be achieved through a high degree of reliability and easy maintainability.

Aerodynamics:

Future aerodynamic trends are directed towards vortex lift, high angle of attack capability and weapon integration and separation techniques.

Propulsion:

The propulsion industry is presently confronted with the technical realisation of many high expectations with respect to higher thrust to weight ratios; dry operation; low speed/high angle of attack capability; increased bleed air and auxiliary power; vectored thrust; simplified control and all with lower costs, longer life-time and simplified maintenance.

Structures and Materials:

The key problem with the new materials is the production cost, which still has to be lowered, combined with increased damage tolerance and simplified repair schemes. Future trends are higher temperature resistance and simpler production methods for the basic materials.

Guidance, Control and Avionics:

Future trends will concentrate on more mission-oriented flight control systems, care-free handling capabilities and highly integrated avionics (particularly direction of fire/flight control). A major problem for future research remains "situation awareness", where the integration of new sensors offers high returns.

H.WUNNENBERG
Co-Chairman,
Programme Committee &
FMP Member

ACKNOWLEDGEMENT

The FMP programme committee wishes to acknowledge the major contribution to this symposium by other AGARD panels and particularly the involvement of the following who attended and contributed to programme committee meetings:–

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ACKNOWLEDGEMENT

The Flight Mechanics Panel wishes to express its thanks to the Italian National Delegates to AGARD for the invitation to hold this meeting in Treviso, Italy; and for the facilities and personnel which made this meeting possible.

Le Panel de la Mécanique du Vol tient à remercier les Délégués Nationaux d'Italie auprès de l'AGARD de leur invitation à tenir cette réunion à Trevise, Italie; ainsi que pour les installations et le personnel mis à sa disposition.

CONTENTS

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*Printed in classified publication CP 409 (Supplement)
†The material presented in paper 23 is contained in AGARD AR-228 "Improved Guidance and Control Automation at the Man-Machine Interface". NATO Unclassified, 1986. (The findings of AGARD GCP WG 07).

KEYNOTE ADDRESS

by

Lt. Gen. Eng. L.Giorgieri

Ladies and Gentlemen,

It is with great pleasure that I welcome you to this 68th Symposium of the AGARD Flight Mechanics Panel.

The subjects which will be presented by so many well-qualified experts address one of the most fascinating topics which can be debated today in an aeronautical forum, that is, the present and future of combat aircraft from various points of view. It is therefore with great interest that all of us will follow the papers which have been submitted and which will give you a panoramic view of what is being studied and realized today in several countries of the Atlantic Alliance in the sector of combat aircraft. We cannot omit our thanks to this vital organization — AGARD — which, since its foundation so many years ago, has gained so much goodwill in sponsoring these periodic meetings of the major aeronautical experts from both sides of the Atlantic.

The subject of this symposium seems to me to be particularly interesting: "The Improvement of Combat Performance in Present and Future Aircraft". Why is it continously necessary to seek an increase of performance in this sector? The question, even if a little rhetorical, is not without importance. It is, in fact, not only a question of simple technological fallout as a function of technical and scientific progress, but rather a continuously developing competition with the objective of improving even more the cost-effectiveness of available weapon systems or those under development.

All countries have finite budget availabilities to be dedicated to defence, and this defence is the more credible the higher the cost-effectiveness of the equipment used. The parameters of effectiveness are found in the types and quantity of equipment and in the characteristics and performance of the platforms used to the best advantage. By optimizing the combination of equipment and performance, new operational philosophies emerge which can materialize as new military requirements formulated by the operational staffs to better meet the military needs of their country. This is possible by innovative mid-life improvements of existing weapon systems, or by the design ex novo of new systems. In fact, if the defence requirement becomes more stringent, the effectiveness of available instruments is consequently decreased and this is acceptable down to a minimum point beyond which modernisation is necessary.

In the last few years there has been an increase in numbers of aircraft of opposing forces, and these have become more competitive as on-board equipment has improved which has helped to quickly overcome the qualitative gap of the past. Possible aerial combat measures against these machines will require operational capability in an extremely dense electromagnetic environment to reduce the efficiency of sensors installed in Western aircraft of the past generation. If then one looks at the defensive capabilities of the Warsaw Pact countries, to evaluate the probability of success of an air attack against internal targets to reduce their remaining offensive capability, it is seen that these countries appear to have effective surveillance networks capable of scanning the entire radar electromagnetic spectrum, making more and more problematic the planning of a penetration mission.

Defensive and offensive Western equipment must be forged, foreseeing hypothetical (though unwanted) battles in more and more difficult conditions, which requires continuous innovative efforts. But modifications to aircraft already in the inventory, or new aeronautical programmes, require heavy expenditures for national economies, and therefore any decision on this matter must be carefully pondered.

With my current responsibility for Aeronautical Procurement in the Ministry of Defence, I have the opportunity of feeling continuously the pulse of aeronautical programme cost trends, ever more complex, whilst continuous contacts with the General Staffs allow me to follow the evolution of the threat which represents the main factor in the definition of the requirements themselves.

I have been able to see that this evolution of the threat has become faster so that our aircraft, conceived to operate effectively over a span of 20 years, risk becoming operationally obsolete a lot earlier, mainly in the avionic field and particularly regarding sensors. Therefore, whilst the aircraft as a platform remains unchanged in performance and flight qualities, as a weapon system it is forced to follow the changing threat through mid-life improvement of its sub-systems, both in strictly technical and in geographical and political terms, which are much more complex.

Amongst the titles of the papers that will be given, we see this important chapter of updating of existing aircraft capabilities.

However, if the modifications required to meet new exigencies are too extensive, one may be compelled to acquire a new system. It is here that every administration is confronted with the dilemma either to continue to invest in existing equipment or to replace it. Only analyses of cost-effectiveness can show the choice to be taken, provided that they take into account the effectiveness of the military instrument, the needs of the industrial content connected with it, and of all the various items of cost, that is, development, industrialisation, production, maintenance and finally disposition of the equipment. In any case, whether we are confronted with a weapon system mid-life update or the problem of realising a completely new machine, one can see the strong reliance of designers on the most recent technological resources made available by basic research.

Today a combat aircraft is required to operate in the presence of multiple targets, in a hostile electromagnetic environment, and without any fundamental contribution coming from outside; that is to say, in the final analysis, it must have available equipment which will allow it to carry out the foreseen mission, completely autonomously if necessary.

Performance, in terms of war load to the target or manoeuvring capability, increases with the lightening of structures, made possible by the use of new materials such as glass and carbon fibres, with the increases of temperature which can be imposed on turbine blades and combustion chambers, and with the utilisation of aerofoils and shapes with low drag also in the transonic zone, whilst the capability of carrying out attacks further away is increased as is the ability to oppose the enemy's sensors with electromagnetic, optical or optoelectronic decoys.

The development of a miniaturized technology for controlled energy emission in radio frequencies, and for the analysis of the signals that can be detected, has made available within the slender body of a high-performance aircraft further capacities for intervention, amongst which predominates the possibility of acquiring moving targets, both on the ground and in flight, even at great distance, thus allowing the fullest utilisation of the potential qualities of the air-to-air missiles available today. All this is of particular importance if one considers that an aircraft with a longer "arm" can carry out an attack from advantageous positions because it is outside the reaction sphere of the aircraft under attack, that is to say, outside that volume within which the law of large numbers establishes exchange ratios tending to 1.

There is a further new scientific sector which is having a significant effect on future combat aircraft; it is that of passive sensors which, by silently exploring the electromagnetic spectrum from radio frequency to the ultraviolet band, supply useful, vital information during all the phases of the mission without revealing the presence of the aircraft even in bad meteorological conditions. Finally, equipments begin to be realised which increase the capability of that most important of human sensors: sight! So-called "visionic" equipments can penetrate the darkness of night, or perturbed atmosphere, and allow the pilot recognize a runway without lights, and fixed or moving targets. Operations thus made possible can also be carried out in the passive mode (that is, without emissions which may attract the attention of the enemy), thereby achieving increased survivability of the aircraft which can further increase its overall probability of success if it also reduces signatures caused by other energy emissions. Thus it is that in new aeronautical projects these aspects are taken care of by covering *in parallel* areas such as:

- the reduction of the equivalent radar surface;
- the reduction of IR signature;
- the reduction of visible band signature;
- the reduction of acoustic signature.

What we have said so far confirms the tendency seen on modern equipment to use ever more sophisticated technologies for miniaturisation which permits, within on-board weight and volume limitations, a growing number of specialised and sophisticated functions and allows *great flexibility of utilisation and role.* We see, ever increasingly, aircraft with air-to-air engagement and ground attack capabilities which achieve very high precision and performance in two technically very different roles. The same machine, carrying weapons of diverse types, and with extremely fast reconfiguration time between a mission in one role and that of another, can effect two interventions of different types, because its sensors and integrated systems for signal analysis and data processing so allow even if its architecture, shape of wing, and powerplant are more typically specialized for a single role.

Today's avionics therefore make possible a different concept of the multirole aircraft with favourable cost-effectiveness ratios. It is in fact possible to state that, with the same economic allocations and times available for upgrading or modification of a weapon system, often one obtains *greater benefits in operational terms* by concentrating on black box improvements rather than extensive work on the structure and powerplant.

What I have said should be taken in relative terms, because a weapon system is a homogeneous and integrated unity, so that every modification reqires verification of the entire design. One can, however, use the example of the Tornado aircraft, which, with its basic configuration for penetration and ground attack, validly demonstrated by the results achieved to date, even in international competitions, can also carry out an efficient anti-ship role with minimum avionic modification, and can become a powerful long-range CAP interceptor with modification which, in this case, extends to the acquisition, aiming and armament launch systems and the development of thrust. Furthermore, the various versions permit great benefits in a standardized logistic structure.

There is no doubt that the realisation of the air defence variant of Tornado did therefore cost less, in life cycle cost terms, than the expenditure necessary to develop and acquire a new specialised machine, and it is equally interesting to note that the interceptor so achieved has become available in a very short time, having benefited from that characteristic of electronic systems of having development, modification, and finalisation times which are much faster than parallel changes in the airframe and engine fields. In terms of performance, one can observe that an increase, for instance, of useful load capability of the order of 20%, or a parallel reduction of specific fuel consumption, costs more than doubling the offensive capacity in terms of radar range or number of targets that can simultaneously be kept under control or attacked.

The above appears to be connected also with the fact that the progress which can be achieved in the traditional areas of flight mechanics, propulsion and structures, are less "explosive" than the sectors in which a new knowledge of the intimate nature of matter has opened areas practically unexplored as in the sector of electronics and optics, both coherent and incoherent, with the relatively easy realisation of equipment with functions, information horizons, and operational capabilities which are much wider and more effective.

In this particular historical moment, whilst research must follow the new paths indicated by thrust vectoring, propfan, negative sweep wings, one has undoubtedly immediate operational benefits from the utilisation of pulse-doppler techniques, of CMT sensors (telluride of cadmium and mercury), of distributed computerized systems, of data distribution on electrical bus or, better, by fibre optics, of integrated cockpit presentation and ergonomic and instinctive controls.

In the field of possible examples of the up-dating of the vital elements of a weapons system one may notice, amongst the various papers to be read, one presented by an Italian group upon the F104S aircraft. This elderly aircraft is a demonstration of how a good platform, with performance still worthy of respect today, can have the potential to allow an updating operation of its avionics and armament, still extremely interesting from the point of view of cost-effectiveness, and can provide a valid response to those duties assigned by the Alliance to Italy.

However, the most fascinating aspect of this Symposium is, naturally, that covering the new programmes where tendencies and results from so many diverse sectors converge simultaneously and become concrete concepts in the realisation of a new machine. And it is this "harmonisation" that is the most complex and interesting part.

A rapid run through the titles, demonstrates that not one of the significant areas has been omitted, or forgotten, in the works which will be submitted to this Symposium. A further motive which makes this meeting particularly interesting to us in Italy, and to some other European countries, is the fact that we are now launching the international programme, EFA, to realize a fighter which should be in service in the years 2000 and which should therefore "harmonize" within itself those concepts and results deriving from various sectors like aerodynamics, propulsion, avionics and, certainly not last, equipment. The EFA programme will be, as is well known to everybody, an international programme in the wake of the MRCA Tornado, that first great European operation in the Military aeronautical field. I have defined it a "great" operation, not by chance, and not only because of the number of aircraft involved or the validity of the product which has resulted, but for the indisputable "Europeanising" function that the realisation of this aircraft has brought about, both in industrial and operational terms. Norms, construction standards, manufacturing processes, training syllabuses of crews and technicians have been made homogeneous, if not unified, in a part of Europe, overcoming in many cases existing superstructures and national procedures. Without any doubt it has been an important operation which has required great efforts and heavy financial burdens, but it has created that connective tissue in part of Europe upon which, so much more easily, future collaborations can be superimposed, like EFA, which we believe — indeed we are sure — will not only be a magnificent aircraft but will increase even more this unification process between nations which has been so helped already by Tornado.

But apart from these merits, which may seem idealistic, a clear financial and industrial reality exists in countries such as Italy. The realisation of sophisticated machines of elevated technological level involves extremely high non-recurrent costs, so much the higher, the higher the new technological content to be developed, and in the case of an aircraft of the category of EFA it is obviously extremely high, given the type and the level of threat which it will be called upon to counter. It follows that the non-recurrent part of the costs to be spread over each aircraft can become acceptable or bearable for countries such as ours, on condition that the number of machines is extremely high, much beyond the requirements and possibilities of any single country. This is something, of course, which is very obvious to an audience such as the one that I am addressing today.

I wish rather to emphasize an aspect of great importance, which is correlated to what I have just said, on international collaborations. It is, that the international way is not the sole solution for all aeronautical programmes; it became necessary only for the most ambitious ones, such as EFA. The way exists for a whole series of programmes of variable complexity which can still be realised, even nationally. In particular, one could take the example of the approach followed for the AM-X programme, a tactical support aircraft developed by Italian Industry for the Italian Air Force, the foreseeable success of which has led to an external bilateral collaboration with Brazil. This solution, realisable within the technological and financial possibilities of the country and drawing upon know-how in great part already available, proved from the first prototype phase to be extremely valid within the limits, naturally, of a certain type of missions and for a given threat level.

In closing, I would like to say a few more words on what we are about to hear.

Aeronautical development cannot, within limited budgets, find an ideal development environment, but one must have the courage, beyond financial possibilities, to launch programmes in which, more than improvements, one can see a revolution. This phenomenon, which can occur only periodically, for obvious reasons, finds in this forum, in the paper on the X-29 Programme, one of its most interesting examples and it is also a first for European forums. Once again our American friends present themselves to the aeronautical world with ideas and technical solutions of great interest and prospect, even more so bearing in mind that in the United States the ingeniousness of technicians, the strength of the technical, scientific and industrial organisation, as well as political support, pull very often in the same direction.

Due recognition of what the United States represents in the aeronautical field cannot allow us to forget the contribution of papers presented to this forum by other European countries. France and the United Kingdom, leading countries in Europe, are here with a large quantity of papers on various subjects, which reflects the vastness of their interests and involvement in all fields.

In closing, whilst thanking again the AGARD organisation, which has given us this opportunity of meeting together, and thanking all of you for taking part in this forum, I wish everybody a useful working week.

AD-P005 611

COST ANALYSIS OF AIRCRAFT PROJECTS

by
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SUMMARY

The paper reviews the effect of advancing technology on the cost of past aircraft and the implications for the future. The validity of historical records for forecasting a future dominated by technological change and the consequences of continued escalation are discussed. It is argued that more priority needs to be given to the reduction of support cost and a way of looking at this as a direct contribution to military capability is suggested. The role of operations research is briefly emphasised and a more deliberately evolutionary approach to the production of aircraft is advocated.

INTRODUCTION

The cost of improvements in performance has become an increasingly important issue over the years and it is a privilege for one whose principal concern is forecasting the costs of future projects to be invited to speak at a symposium of improvements to performance. It is also reassuring to see cost mentioned so many times in the description of the symposium. It was not always so - it is a consequence of an apparently inexorable rise in defence equipment costs which was recognised some years back as likely to completely counterbalance the benefits of advancing technology in countries with constrained defence budgets. Even so, I find myself one of very few speakers who explicitly refer to costs or economics in the title of their papers. I have taken the view, therefore, that I ought, as far as I am able, to provide you first with a review of the cost implications of advancing technology as applied in new projects which can act as a background for your later discussions of the technological opportunities available for improving current aircraft. To do so I shall take advantage of a great deal of work done by colleagues in my directorate and by others, to all of whom I am most grateful, but the views I shall express are my own and not to be attributed to the Ministry of Defence.

It has been usual in talking about costs in the past to concentrate almost exclusively on acquisition costs. But certainly, in the UK, and I imagine in most countries, support costs have become recognised as increasingly important so that nowadays investment appraisals of defence projects are required to compare whole life or life cycle costs. It is difficult enough to forecast acquisition costs but forecasting support costs is even more difficult because the timescale is so extended. Nevertheless, the importance of support and operating costs cannot be over-estimated and I shall return to this theme later.

THE BASIS FOR COST FORECASTING

I should also make some preliminary remarks about the basis for forecasting future costs. Most of us here are engaged in research and development; in other words, professionally engaged in making the future - a future we all tend to conceive as quite different from the present, let alone the past. However, all the evidence available as a basis for forecasting is, obviously, taken from past records and is, therefore, open to the criticism that it can be of little guidance to a future so strongly influenced by dramatic technological advances quite unparalleled previously.

In defence of the value of historical records, it must be said that there have been plenty of advances in technology just as dramatic as those which the future now seems to offer. A knowledge of how these were incorporated in subsequent production is a guide to how current advances are likely to be incorporated - and an indication of how much attitudes must change if the past is not to be repeated. For example, a careful analysis of the way changes in technology have their effect shows that they have frequently failed to achieve their potential as quickly as was prophesised by those most concerned with their gestation. It is not always appreciated nowadays how long it has taken for the fly by wire concept or for carbon fibre materials to be used in production aircraft. Both of these revolutionary advances were being heralded in the early 1960s as likely to have a radical influence on aircraft within a few years. Thus, hard evidence of the statistics of past cost escalation and programme overruns, as opposed to personal anecdote, can cast a great deal of light on the probable progress of emerging technological change even when this involves entirely new principles. It is necessary, however, to qualify this last remark. All forecasts based on evidence from the past - the only conceivable quantitative evidence - involve the assumption that the organisations concerned will behave exactly as in the past. Thus, such forecasts are eminently falsifiable. For example, all aircraft suffer from weight growth during development, principally for two reasons; a natural failure to fully appreciate the difficulty of meeting the original specification and a tendency for the requirement to increase during development as perceptions of the threat and of the aircraft's role change (Figure 1). This weight growth leads to cost increases and delays which are to a considerable extent avoidable if, instead of being regarded as of paramount importance, the specification is relaxed in the interests of maintaining cost and timescales. Thus, where it is clear that projects are to be managed in this way, it is reasonable for cost forecasters to modify estimates based on historical evidence. Unhappily, good intentions are not enough - in most countries they have been a universal feature of decisions to enter full development. To some degree, therefore, cost forecasters find themselves in the position of Cassandra in Greek mythology - gifted with knowledge of the future but doomed never to be believed!

Of course, cost estimates have not always been accurate enough to be of much use. This is illustrated for UK aircraft projects in Figure 2 which shows the ratios of final development cost outturn to estimates made at the start as a function of the date on which full development commenced. This is an updated version of an illustration from a paper by one of my predecessors (1). A similar pattern based on US experience has been demonstrated by Augustine (2). The mid-1960s clearly represents a turning point after which much greater efforts were made, not only to estimate costs more accurately, but also to control them better and it is at about this time that my own group and similar ones elsewhere were formed.

COST ESCALATION

Nevertheless, it cannot be said that the formation of independent cost estimating groups did much to halt the inexorable rise in the cost of successive generations of aircraft which, although widely recognised, is probably best documented and explained by my colleagues Kirkpatrick and Pugh in their 1983 Royal Aeronautical Society paper (3). They point out that apart from the technological arms race between opposing nations or alliances, there are several other vicious circles which together accelerate the trend towards higher unit costs. More effective aircraft tend to have higher development and unit costs in spite of the improved methods of manufacture which become available. The increase in development costs of aircraft projects means that a government tends to fund new projects less frequently and the increased technological step required between genrations further increases costs. Because defence budgets are limited, increased unit production cost means that fewer aircraft can be purchased which reduces the scope for learning and the benefit of production investment so further increasing costs. The overall effect has been a real growth in UPC since the War of about 8% per annum which has been contained only by a compensating reduction in the number of aircraft and of types.

Cost escalation at this rate cannot continue indefinitely and there would seem to be only three possible outcomes:

a. a plateau of capability will be reached or closely approached;

b. the weapon system concerned will be rendered obsolete and superceded by a new and economically more attractive form of defence;

c. in contrast to the above possibilities dictated by external forces, there could be a deliberate policy decision to consciously and successfully resist further escalation by management controls on cost.

Although plateaus of capability are reached from time to time, they have always proved temporary - such is the persistent ingenuity of man. On the other hand, weapon systems have been rendered obsolete by their unaffordability and replaced by more affordable methods of offence or defence. The steam-driven big gun battle ship is a salutory example but it is not easy to forecast when such a revolutionary change will occur. In 1957 Mr Duncan Sandys, then UK Minister of Defence, predicted that combat aircraft would soon be rendered obsolete by much cheaper and more effective land-launched guided weapons. His prediction may yet turn out to be correct in general terms but he was certainly wrong about the timescale. Since that time there have been many declarations of policy at least partly designed to contain costs: for example, the declarations by the UK annual defence white papers to shift the balance of investment from launch platforms, such as aircraft and ships, to the weapons carried by them. These changes have been successful to some degree but they cannot be said to have done more than postpone the crisis.

The crucial problem is not, of course, technology itself, but the way in which it is applied. Many of the technological advances made possible by research can be used either to increase performance or to reduce cost and in some measure to do both. It is, the research scientist or engineer might say, the job of designers and of the armed forces to ensure that research results are applied in the most cost-effective way. For my part, however, I do not think that such a view can be maintained any longer and in this I am clearly at one with the organisers of this conference. For one thing, the issue of cost has become too critical in the maintenance of a credible defence and, for another, the relationships between those engaged in research, in design and as customers in the armed services have now become so close as to make it necessary to consider them an integrated team. In their enthusiasm to see their inventions turned to practical use in new equipment research, scientists have in the past been too inclined to play down the practical difficulties and cost of translation from the laboratory to the production line. They need, therefore, to give much more informed advice on the trade-offs possible between cost and performance and to direct their programmes much more towards the reduction of cost than they have been inclined to do in the past.

LIFE CYCLE COSTS

Moreover, R & D scientists and engineers cannot concentrate exclusively on acquisition costs. It is conventional nowadays to say that it is life cycle cost which is important but I am inclined to be more specific and say that emphasis must be much more on support and operating costs than it has been in the past. Indeed, it has often seemed that the priority for reducing cost has been directly proportional to the imminence of the expenditure and inversally proportional to its size. Thus, the priorities have been, first, to reduce development cost and the second to reduce production cost (which is in total usually larger than development cost) and only third, if at all, to reduce support and operating cost, although that is usually much larger than the other two put together. The reason for this is the obvious and immediate pressure of budgets, so for this reason alone insufficient investment is usually made during development to ensure high reliability and therefore low support costs. But the problem is exacerbated by the absence of any real basis for deciding where, or how much money it is worth spending during development in order to reduce in-service costs. Such relationships have been strenuously sought but so far as I am aware no useful ones have been found and I am inclined to think that the problem is intrinsically insolvable at the design stage. Advocates of early investment are nevertheless fond of pointing to graphs which show that most of the life cycle cost of projects is committed by decisions taken very early in their lives and concluding that this is when greatest attention should be paid to, say, increased reliability. Unfortunately, this is true only in a trivial sense - for instance the decisions to develop a new combat aircraft undoubtedly commits a much larger sum of money than a decision to develop a trainer. At the earliest design stage, the most one can say is that the more tried and tested the equipment included in the system, the greater its reliability is likely to be. Indeed, the most powerful influence on reliability and maintainability at this stage is likely to be the quality and experience of designers and the extent to which they keep that in the forefront of their minds as they pore over their drawing boards - or nowadays their computer terminals. These are not intrinsically expensive activities since metal has yet to be actually cut - although it might suggest that good designers should be very highly paid! It is possible to say *from* experience of earlier projects what parts are likely to have a high support or maintenance cost but it is not possible to say precisely *how* much money it will be necessary to spend in order to achieve a prescribed level of reliability. The earliest time at which it is possible to plan to spend specific amounts of money with a reasonable certainty that reliability will be improved is when test results from representative equipments become available and the reasons why these fall short of targets is known. The general and, I fear, impractical, advice to spend money on reliability early in a radically new project has tended to distract attention from the opportunities for reducing support costs which occur as data becomes available during the later stages of development, production and the early stages of operational use. Figure 3 shows a remarkably linear relationship between failures per flying hour and aircraft empty weight for a range of aircraft with in-service dates between 1955 and 1980. To emphasise the point, Figure 4 shows the number of defects per flying hour per unit mass is virtually independent of year of entry into service. The aggregated data does, however, hide the influence of developments in avionics. The period 1955-1980 covered by Figures 3 and 4 has seen huge reductions in the cost of basic electronic hardware and similarly large increase in its reliability per function computed. These improvements have been almost, although not quite, negated by the demand for vastly more electronic functions to be incorporated in aircraft and by the unreliability inevitably associated with much more complicated systems. This growth in demand for electronics is clearly seen in the proportion of aircraft unit cost allocated to avionics. This has risen from about 10% in mid-1950s combat aircraft to about 30% for current aircraft.

If support costs are to be reduced substantially, the designer must be encouraged to choose the approach most likely to lead to that end. Unfortunately, the convention of discounting future expenditure when comparing alternative options for future projects provides little incentive for decision-makers to give a high priority to reduced support costs and this attitude is bound to be passed on to designers. However, there is another way of looking at operating and support costs which may be helpful because it emphasises their contribution to effectiveness. It is a common-place that reduction in acquisition costs means that more equipment can be purchased. The same is true of reduced operating and support costs - with the added feature that, unlike acquisition costs, they persist throughout the life of the equipment. Most defence ministers are constrained to a fixed budget - usually related to the size of GNP - and any change to this involves a major change of government policy. Such a change, if it involves an increase, has a potentially de-stabilising effect on international affairs and so is rarely politically popular. The headroom that exists at any given time between the total defence budget and the cost of operating and supporting the current force can be regarded as a measure of the flexibility of the defence force to respond to a previous under-estimation of the size of the threat by the purchase of increased numbers of equipment or by investment in research as an insurance for the future. Flexibility in the sense of being able to concentrate firepower rapidly at any point within a wide area is a highly valued military capability and one particularly associated with airforces. But flexibility in this new sense is just as important a military capability and one to which every reduction in support costs contributes directly.

At this point, it may be useful to give an impression of the scale and importance of reductions in support cost obtained by improved reliability. If the number of defects occurring per flying hour in the next generation of combat aircraft were successfully reduced by one third compared to current generations of aircraft - and this appears to be an achievable aim - the saving in support cost over the life of that aircraft would be as large as its total development cost. In terms of flexibility to invest the saving would be sufficient to finance the development of its successor or to purchase a reserve of the order of 100 extra aircraft at the end of the planned production line.

OPPORTUNITIES FOR THE FUTURE

Thus, as always, the future holds out the tantalising promise of reduced costs and other authors will no doubt be considering the potential of some quite different kinds of research achievements which have now reached a stage where they can be applied to aircraft in development and production. Composite materials, aluminium - lithium alloys, the so-called "fly-by-wire" technology and CAD/CAM represent advances which are quite different in character. Composite materials, carbon fibre composites to be specific, have, as I have already mentioned, taken a long time to develop and for a good deal of that time their potential for reducing the cost of aircraft manufacture was widely advertised. Nowadays one does not hear this particular virtue mentioned anything like so much as their physical properties and associated potential for improving performance.

The introduction of new materials is generally accepted as risky and risk is inseparable from cost, at least during development. On the other hand, new manufacturing techniques tend to be introduced when it is clear that they have a cost advantage over earlier methods. Since the old methods remain as a fall-back in case the new methods fail to fulfil their promise, the change of method is relatively risk-free (4). The really major risks are associated with such fundamental changes to systems as the current introduction of fly-by-wire technology with all the irresistably tempting opportunities to improve performance that are associated with such a change. It is changes of this type that have in the past mainly driven up the cost of combat aircraft. Of course, reduced cost and improved performance can go hand in hand as they frequently do in civil aviation where "seat cost per mile" is a recognised performance parameter. It is, therefore, salutory to compare the way in which costs have risen for combat aircraft with the trend for civil aircraft. Figure 5 shows very clearly the way in which market forces have constrained the cost of civil aircraft while the cost per kilogram of the "latest and best" military aircraft continues to rise steeply. Three points are particularly interesting. First, in the 1950s and before, there was little difference between combat and civil aircraft and, second, there is a class of military aircraft whose costs have behaved similarly to those of civil aircraft: those where, for various reasons, realistic constraints are imposed on the cost of the aircraft or the time for their development is highly constrained. Examples are Jaguar and Hawk. Third, it is note-worthy that the rise in specific cost of advanced combat aircraft is very similar to the rise in the cost of complete avionic fits shown in Figure 6 although the scatter is much greater.

This conference, however, is concerned with suggesting opportunities for restraining the depressingly upward trend which has characterised defence equipment costs. The key lies in operations research or, as it is also sometimes called, operations analysis. In civil aviation, competition and the profitability of the company provides an effective curb on rising costs as Figure 5 shows. In defence, competition has seemd to make matters worse partly because its main manifestation is the competition between opposing alliances. Competition between firms cannot have a significant restraining effect on the general rise in a market place complicated by international political considerations, the variety of requirements of different national air forces and the sheer size of the investment required in relation to the defence budget or even medium sized nations. There has been a persistent hope that the deficiencies of defence markets in relation to civil markets could be corrected by the (timation of effectivness in universally applicable terms, analogous to money, and similarly capable of arithmetic manipulation. Such a measure - or, failing that ideal, several measures - of the benefit of the output of defence might, when compared to cost, ensure that defence funds are always deployed efficiently. This aim has so far proved elusive and indeed the definition of a satisfactory single measure can safely be dismissed as remotely unlikely. Nevertheless, there is everything to be said for greater determination to assess the benefits to be gained from increasingly complex aircraft in comparison with their costs. This requires, not only a close interaction between operational research scientists and decision-makers in airforces - which has always existed - but a similarly close interaction between OR scientists and research and development teams - which has been much less usual.

THE WAY FORWARD

This brings me to a discussion of practical means of containing the rise in both acquisition and support costs which is the main theme of this symposium. One method much advocated is international collaboration which undoubtedly has a substantial political attraction as well as reducing acquisition costs. But the collaborative approach,while mitigating the effects of escalation, does not deal with the fundamental problem. A promising approach for European nations is greater reliance on technology demonstration - the idea that new technologies should be demonstrated to the level of performance required before full development of a new project begins, and by this means risk will be much reduced. Development then becomes concerned primarily with improving reliability and reducing costs, and a much sounder basis for assessing cost-effectiveness exists. A good deal of progress in this direction has been made in the UK in recent years but it is not easy for two main reasons. First, to be successful it requires substantially more expenditure than the research phase, but is similarly uncommitted to particular future projects. Second, it inevitably seems to imply a slower introduction of new technology into service and thus invites resistance on the grounds of failing to keep up with the threat. This is almost certainly not the case - if only because, again on the evidence of the past, increased reliability and availability of the systems is likely to more than compensate for any deficiency in theoretical performance.

The theme of this symposium emphasises the improvement of existing aircraft as an alternative to embarking on totally new concepts. In fact, aircraft have increasingly tended to remain in service for much longer than was originally planned because of the escalation of replacement costs and have been subjected to numerous improvement programmes to delay their obsolescence. But there are other reasons why current aircraft are improved. In war-time, there is frequently no time available for new development so a succession of improved versions or marques evolves. In peace-time the recognition of alternative market opportunities can produce the same effect. The cost savings have often proved substantial. Table 1 shows the reductions in production cost of successive improved marques of some UK World War II designs and it should be noted that the costs given have been corrected for the effects of scales of production. In the same table, the reductions in cost of successive marques of several more recent US designs are shown. The A-4 aircraft is included as a warning to show that such an approach will not always produce saving - obviously it depends on how exotic the improvements are and how difficult it is to fit them in existing airframes.

It is only a small logical step from this to propose a philosophy of development which assumes, ab initio, that production aircraft will evolve through a number of marques. The adoption of such a philosophy would mean designing next generation aircraft with an explicit allowance for growth of capability but to be produced in the first instance with only modest technology advances. Production might be planned to take place more slowly over a longer period than has been usual in the past - improvements being phased in gradually. This approach depends to some degree on the assumption that improvements in the weapon system as a whole are more likely to be satisfactorily achieved by improvements in weapons and avionics than in the basic aerodynamic and structural design of aircraft. But the approach has the disadvantage that either a variety of different marques must be maintained in service simultaneously or a continuous programme of retrofitting must be accepted. Such is the scale of modifications and mid-life improvements at present, however, that this disadvantage may be more apparent than real. Overall, the approach seems to have a good deal of promise if there is sufficient determination to exercise restrain during definition and development.

CONCLUSIONS

In conclusion, the great advantage of modifying existing aircraft to improve their performance, as opposed to designing entirely new aircraft, is simply that both the costs and performance of the baseline aircraft are well known - as indeed are its weaknesses. There is, therefore, a sound basis for estimating the consequences of changes to one part of the aircraft or another. If reductions in support and operating cost are required, for example, it will be clear where the necessary investment needs to be made and there will be reasonable confidence in assessments of the benefits. Of course it may not be possible to incorporate the improvements offered by technology in an optimal way and this is particularly likely to be the case with new materials. It could, on the other hand, be argued that it is precisely this search for optima which helps to fuel cost escalation. However, there can be no guarantee that the modification of existing aircraft can solve the cost escalation problem. For instance, squeezing extra capability into an aircraft not originally designed for it can be exceedingly expensive and the introduction of new designs to replace ageing ones cannot be put off indefinitely. In the last analysis, costs can only be reduced if there is a determination to do so. There is no substitute for a realistic assessment of costs as well as effectiveness in the knowledge that in different circumstances different solutions will be indicated.

REFERENCES

1.	Harrison, J E A	Aerospace cost prediction - the way ahead. The Aeronautical Journal, May 1977.
2.	Augustine, N R	A viewpoint of industry - Journal of Cost Analysis Volume 2, Spring 1985.
3.	Kirkpatrick, D L I & Pugh P G	Towards the Starship Enterprise - are the current trends in defence unit costs inexorable? Aerospace, May 1983.
4.	Pugh, P G	"Who can tell what may happen?" - risks and contingency allowances RAeS 1985 Spring Convention.

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TABLE 1 - REDUCTION IN COSTS (UPC) OF SUCCESSIVE MARQUES

UK World War II Designs

UPC at CuAv100 and 9/39 etc.

MARQUE	BEAUFIGHTER	BLENHEIM	FIREFLY	HALIFAX	MOSQUITO	WELLINGTON
I	10.68	10.56	18.02	20.80		19.02
II	7.26				8.69	
III						
IV	6.17	7.04	11.99		7.99	
V		7.54				
VI			10.96		7.97	8.29
VII						
VIII				13.36		
IX				13.10	7.04	
X						10.77
XI						
XII						
XIII						
XIV						
XV						
XVI					6.33	
XVII						
XVIII						
XIX					6.75	

More Recent USA Designs

UPC at CuAv100 in $M,FY80

MARQUE	F-8	F-86	F-III	F-4	A-4
A	4.528		23.239	9.574	1.945
B					
C				5.628	2.135
D	4.069	1.387	23.243		
E				5.842	2.638
F		1.047	20.713		
G					
H					
I					
J				5.744	
K					
L					3.659
M					

Note: All costs at constant ec and at CuAv100 ie
LEARNING EFFECTS HAVE BEEN EXTRACTED

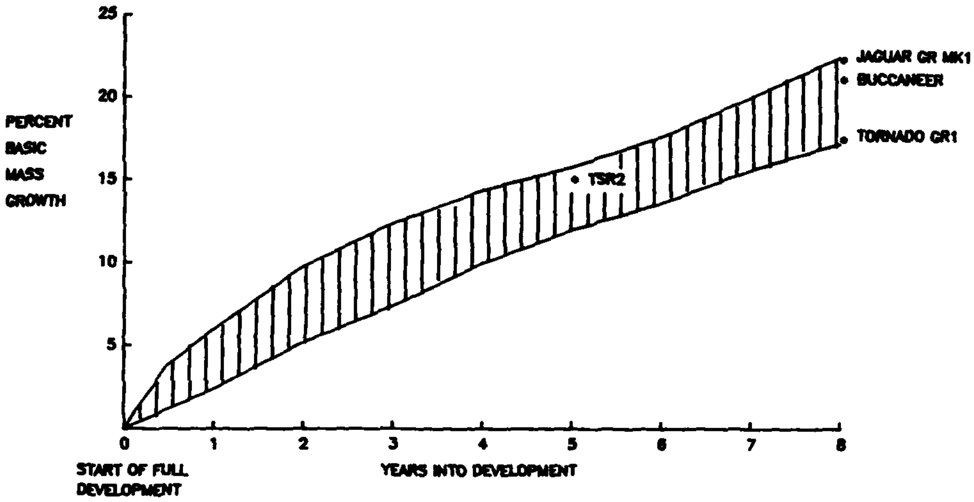

FIGURE 1. AIRCRAFT MASS GROWTH.

FIGURE 2. IMPROVEMENTS IN FORECASTING ACCURACY
MILITARY AIRFRAME DEVELOPMENT.

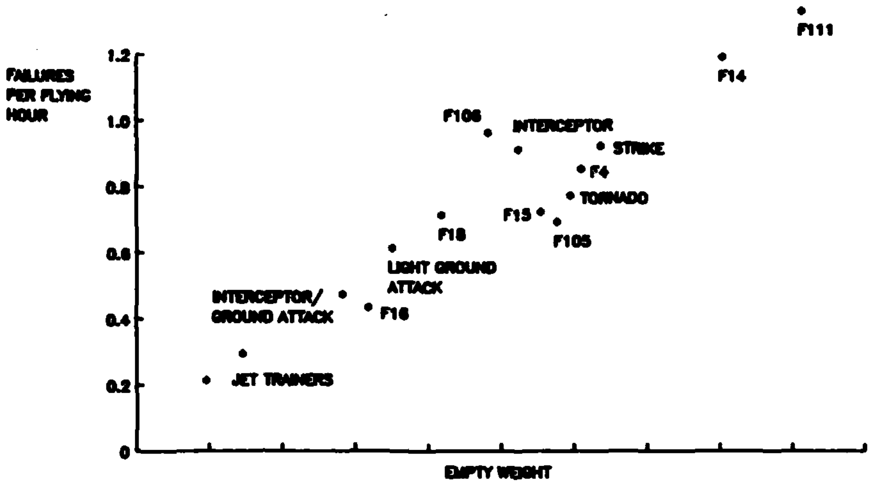

FIGURE 3. FAILURE RATE AS A FUNCTION OF EMPTY WEIGHT.

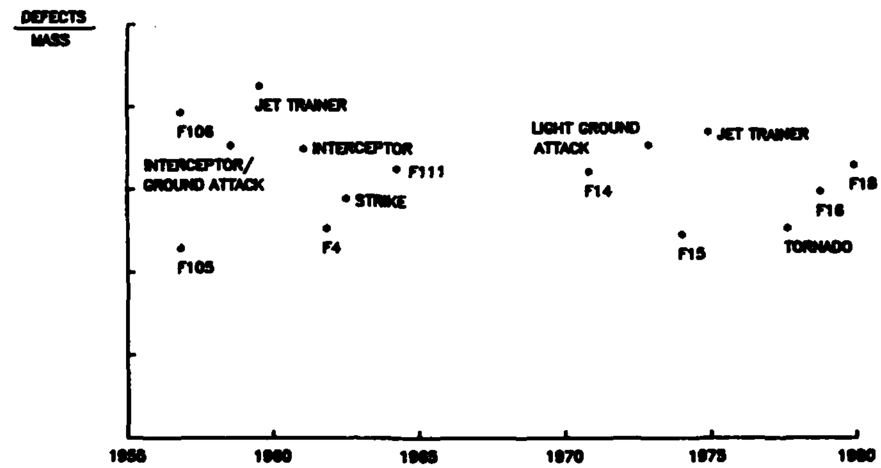

FIGURE 4. TRENDS IN SPECIFIC RELIABILITY.

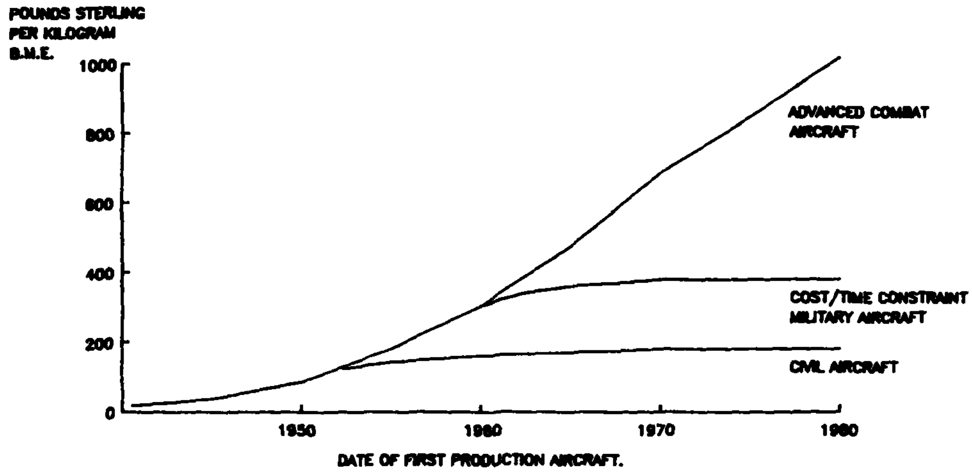

FIGURE 5. COMPARATIVE COST TRENDS FOR CIVIL AND MILITARY AIRCRAFT.

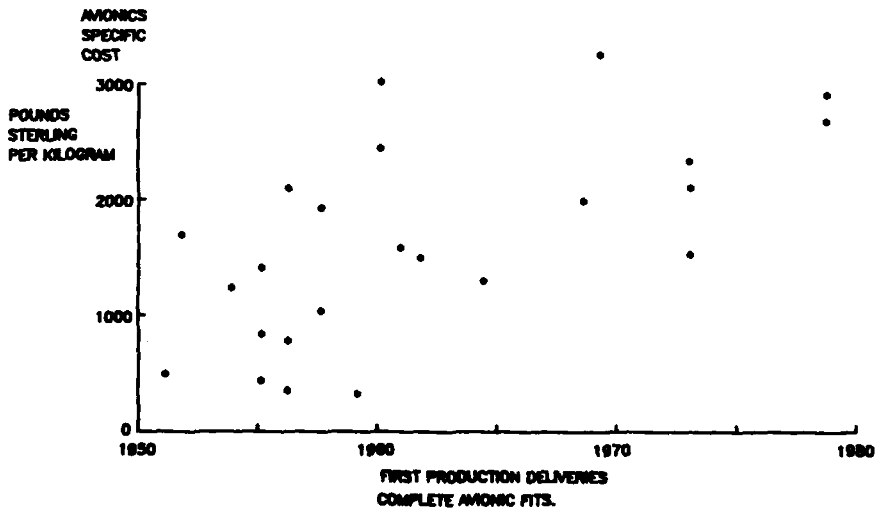

FIGURE 6. TRENDS IN THE COST OF AVIONICS.

AD-P005 612

Performance Improvement of Airborne Weapon Systems
Methods, Scope and Limitations

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Summary

This paper defines performance improvement and the necessity to evaluate the overall and operational system performance improvement by use of systems assessment methods. These methods are briefly discussed using simple examples of former evaluations.

Introduction

System improvement measures are part of the life cycle of all complex airborne weapon systems. These measures are aimed at keeping the system abreast of the times, i.e. adapting it to changes in use or changes in the threat to be countered.

As a rule these measures do not constitute an alternative to new development. But in conjunction with life extension programmes they are able to bridge budgetary gaps or shift the introduction of a new system to a point, where new technologies may be incorporated with clear advantage. In other words, they may help adjust the in service dates for new generations of systems.

This paper tries to point to the problems of performance improvement in assessing the measures taken from the viewpoint of an overall systems concept. An operator's view on the subject is given in figure 1. It corroborates the views expressed before.

The discussion concerning financial feasibility of defense systems in view of constantly limited or even decreasing budgets has been prominent for many years. The financial problem has been aggravated by above average cost increases in the defense industry. So there is a very real need for cost reducing meausres concerning development, acquisition and utilisation of operational systems.

In this context performance improvement, especially with airborne systems, has been considered one appropriate approach. This has even led to the belief that performance improvement could in some cases replace the necessity for the development of new systems. This extreme view on performance improvement detracts from the original value and intention of improvement programmes.

For a systems designer systems improvement starts with the inclusion of appropriate growth capability at the early stages of systems design. The life time of systems, often more than 25 years, precludes precise advance krowledge on the changes in threat and utilisation of the system and also of technical progress. Performance improvement is therefore necessary to adapt a system to evolving circumstances.

System improvement can be triggered by various aspects in the operation of an existing system and will consequently have different aims or targets (figure 2).

The first two triggering factors are the most common and important, but the possibility to limit or decrease operating costs will certainly assist in deciding on a performance improvement measure.

A performance improvement programme means planning and realizing selected technical changes aimed at bettering operational effectivity, operational life time, operational flexibility and economy. The military services will have to evaluate these measures with a view to assessing the operational gain against necessary expenditure.

The systems engineer involved will therefore have to achieve a sufficiently accurate prediction of performance and costs. This will include predictions of:

- functional integrity
- performance
- operational characteristics
- reliability
- survivability
- maintainability
- development costs
- procurement costs
- operational costs.

The cooperation of all features and subsystems in the overall system is of utmost importance. The overall system performance should be assessed before a decision is taken to implement an improvement feature.

Although this may sound like a banality experience has shown that the temptation exists to focus one's attention on one technical aspect only and show the performance increase for that part only. This can lead to disappointing results for the system effectivity.

As an example figure 3 shows the typical attack sequence for a manned aircraft carrying a guided missile. Once the decision to take off and attack a target is taken a sequence of actions begins involving a multitude of subsystems which in turn contribute in various ways and with differing precision to the successful operation. Each one of these phases is essential to the mission and cannot be skipped. The weakest link in the chain of systems determines overall system performance. Naturally performance improvement measures should concentrate on these weakest links and by improvement of selected properties enable the system to make better use of the built in capabilities.

Technical Measures

Basically every component of a weapon system can be subject to change or improvement. In order to decide whether an improvement is justifiable assessment of the effect of any one measure on mission effectivity has to be predicted with reasonable accuracy. This prediction and assessment has to be tailored to each case under consideration.

Past cases show that certain subsystems in airborne weapons lend themselves more readily than others for improvement programmes (e.g. weapon subsystems, avionics (hardware and software), propulsion subsystems, sensor systems, fire control systems).

Other subsystems (e.g. airframes, basic engines, missile-guidance subsystems) involve such extensive changes that the improvement expected usually does not justify the expenditure involved.

Prediction Methods

IABG-WT has been for many years working under contract to the Department of Defense on assessing airborne weapon systems starting in the earliest stages of prefeasibility all through to full scale development and also on engineering changes in the utilisation phases.

The experience gained and the tools developed during these studies constitute the basis on which system performance prediction is made. It manifests itself in data collections, computer programmes and simulation facilities and also selected cost prognostic methods. Some examples should serve to illustrate this.

For instance, to evaluate improvements on components of turbo-engines, cycle design computer programmes are available with the help of which changes in components (e.g. LP compressor, HP compressor, turbine stages, or afterburner etc.) and their effect on thrust and fuel consumption can be determined (figure 4).

The figure shows thrust and SFC changes of a derivative bypass engine with afterburner for a changed application. With this type of information a suitable combination of engine parameters can be selected for the new application.

These engine data in turn are the basis for point performance and mission performance calculations performed with an aircraft parametric design programme. Besides determining the absolute achievable performance values statistic variations of design parameters like thrust, SFC or cruise drag can be combined to show performance of a fleet of aircraft as shown in figure 5.

Computer assisted design and simulation of missiles allows to evaluate the influence of modification to missiles and their target acquisition sensors. In figure 6 a simple example is given on the influence of thrust and wing area variation on the shooting range envelope of a surface to air missile system. In this example the greatest change is achieved by variation of the wing surface for altitude range as opposed to a thrust variation.

The associated changes in control surfaces, actuators and control system are rather extensive and make such a change an unlikely candidate for performance improvement.

Another aspect of airborne weapon systems is their survivability in the presence of enemy air defense.

With the help of computer aided vulnerability analysis (figures 7 and 8 here shown on the example of a manned combat aircraft) survivability can be assessed by simulation of different surface to air weapons.

Penetration of fragments through structure and systems gives a measure of damage resulting in a degradation of system integrity. This then can be expressed in kill categories and may indicate the need for geometric regrouping of components in the aircraft or introduction of armour.

Performance predicition, however, would be incomplete if the operation of the system including the man in the loop were not considered.

This leads to manned simulation which, if set up in an appropriate scenario, can prove the overall effectivity from an operational standpoint.

The IABG facility for manned simulation has proven to be a powerful instrument in this type of assessment. With it pilots of the Air Force are able to operationally test a follow on generation of weapon system.

Real time simulation programmes reflecting the features of the system in combination with a projection system, with displays and some representative hardware for example can enable a pilot to test the advantages envisaged for a given missile/aircraft combination. He can under operational conditions try to utilize off boresight and all aspect capability and determine their effect at the same time formulating optimum tactics for the system (figure 9).

Scenario influences prove to level out extreme technical advantages and detailed and correct representation of scenario influences therefore lead to good prediction of the effects of improvement measures under these conditions.

Often improvement programmes consist of the integration of advanced air/air or air/ground missiles into existing aircraft or helicopters. Here it is essential to make sure, besides integrating the hardware by adapting interfaces and controls to the new weapon, that the performances and capabilities of the sensors and target acqusition system are adequately enhanced to handle and utilise the performance of the weapon.

In figure 10 the matching of missile kinematic ranges with target acquisition limitations is touched. On the left side of the diagramme the missile kinematic range is compared at co-altitude for a medium range A/A missile with sensor ranges in a given acquisition mode and in the centre the conditions are shown in a look-down situation.

The right side of the graph shows a similar comparison for a short-range IR-missile as limited by lock-on procedures. This clearly indicates that enhanced kinematic ranges cannot be operationally utilised if the sensor system cannot support the missile appropriately.

These limitations need further testing in manned simulation under operational conditions.

Similar considerations apply in the case of the matching of a navigation system used in the deployment of an air to ground missile system with a pure inertial midcourse phase when released from a manned aircraft (figure 11).

The inertial system of the missile has to be initilized before release. Hereby errors of the aircraft inertial system, the alignment of the missile, the dynamics of the suspension and time dependent navigation errors all combine in the tansfer. The flight of the missile adds more errors and at the lock on range there results a position and attitude error which hopefully still allows the seeker system of the missile to acquire the target. Transfer and alignment as a rule contribute the largest error. Therefore improvement of the navigation platform in the aircraft alone will hardly better overall performance.

A few remarks on cost prediction may seem in order. IABG makes use of a number of computer aided prediction methods. However results have to be carefully matched to the conditions of the specific case in hand. This requires experience of the costing engineer. Also economic conditions influencing the case must be carefully checked. The problem of using all available data of development, procurement and utilisation is aggravated by the fact that these phases usually are financed by separate budgets and this makes an overall decision on performance improvement very complex.

Costing a utilisation phase moreover requires sufficiently accurate data or prediction of reliability and maintenance indices. Here much improvement is needed in methodology. Typically prediction, validation and actual operational values differ greatly as shown in figure 12 for several systems according to two sources.

Examples

From a multitude of cases let us consider two improvement programmes for airborne systems.

The combat aircraft F-4F has, since its introduction into service in the German Air Force in 1973 been subjected to serveral modifications. These modifications mainly covered weapons management, fire control computation and associated software which resulted in significant improvements in air to air and air to ground capabilities.

At present the integration of modern air to air medium range missiles is being studied together with life extension measures which are considered a prerequisite to the improvement.

Many farreaching suggestions for performance improvement of the F-4F were considered in the years past. The emphasis mainly was on enhancing avionics capabilities.

One suggestion aimed at replacing the J-79 engine by a more advanced engine with higher thrust and less maintenance requirements which also provides higher level of carefree handling.

The physical dimensions as well as the very important air flow value were very close to those of the J-79 and therefore a replacement would surely not have imposed insurmountable difficulties.

The sustained turn rates of the aircraft (figure 13) would be dramatically improved. But other important performance parameters like instantaneous turn rates and handling characteristics would remain unchanged.

Moreover the high expenditure of the integration of a new engine of approximately 50% of the initial procurement cost (considering all factors including inflation rates) make this solution unattractive which would also lead to a costly validation and certification effort.

A second example of performance improvement which has not been approved pertains to the Army's transport helicopter UH-1D.

The proposed modification would have replaced the 2-blade rotor by a well tested 4-blade rotor in conjunction with increased power in the engine.

The engine variants considered increased power output of the existing T-53 engine and also alternatively more powerful engines were investigated.

This type of modification results in a significantly increased payload range capability as seen in the top of figure 14. Another advantage would be the greatly reduced vibration level as shown in the lower diagramme especially for the medium and high speed range.

This modification proved very costly and was therefore shelved.

Conclusions

This contribution tries to place emphasis on the system analysis aspects and prediction possibilities for improvement programmes.

The following conclusions from the view of the systems engineer may be drawn:

- Performance improvement programmes for airborne weapon systems are a necessity because of the long life time of systems and the changing threat situation. Performance improvement generally is linked to life extension measures. Both are most likely when growth capability has been part of the system design.

- Performance improvement cannot as a rule replace development of new systems but may help in bridging gaps in scarce resources.

- The criteria for the assessment of the feasibility and acceptability of improvement measures are known and generally sufficient both concerning performance and cost.

- Careful system analysis of each single measure within the context of the entire system and its operation is necessary.

- Inclusion of the man in the loop in manned systems is necessary to judge overal performance.

- Analysis of performance improvement with respect to expenditure must include all phases:
  development, procurement and utilisation.
  Budgetary structures often make this extremely difficult.

FIGURE 1

o performance improvement and life extension programmes permit
  - at reasonable cost
  - at calculated tactical and technical risk
  - for a limited period of time
  - the enhancement of system performance
  - the extension of operational life
  - the bridging of a phase with limited budgets

o performance improvement of an operational airborne weapon system cannot replace the development of a new high performance, tactically and technically appropriate weapon system; it can at best postpone this development

o development of a new airborne weapon system is replaceable only, if it can be proved that its application can
  - with better adaptation to the threat
  - more effectively
  - at lesser cost

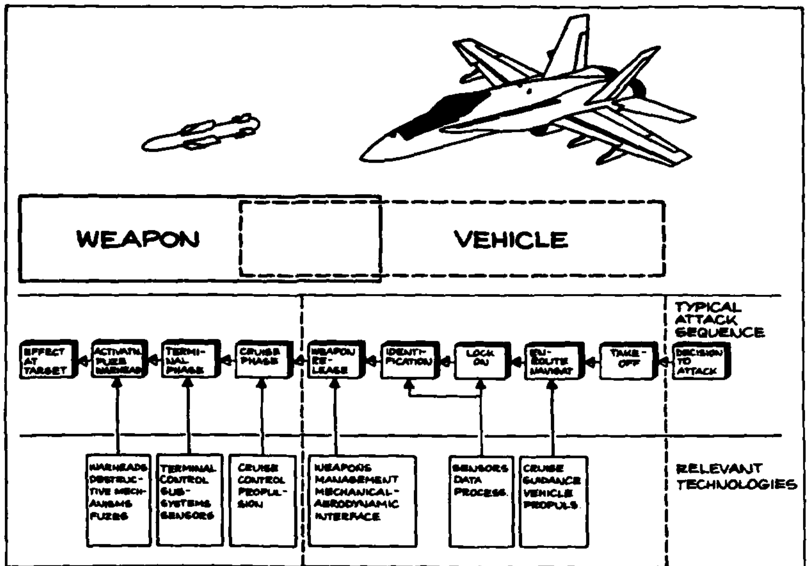
  be taken over by other operational means.

O.i.G. Brunke, Fü L VI 4
150. WT Symposium
Mannheim 1982

FIGURE 2

TRIGGER	TARGET
CHANGED THREAT	PERFORMANCE INCREASE TO COVER THREAT
TECHNICAL PROGRESS	CHANGE IN PERFORMANCE (E.G. AVAILABILITY, PERFORMANCE LEVEL) COMBINED WITH LOWER OPERATING COSTS. ENLARGED OPERATIONAL SPECTRUM
LIMITED BUDGET FOR DEVELOPMENT/PROCUREMENT OF REPLACEMENT SYSTEM	COST SAVINGS COMBINED WITH ACCEPTABLE OPERATIONAL EFFECTIVITY
HIGH OPERATIONAL COSTS	INCREASE OF OPERATIONAL AVAILABILITY AND DECREASE OP OPERATING COSTS

FIGURE 3



SYSTEM ASPECTS - ATTACK SEQUENCE

FIGURE 4

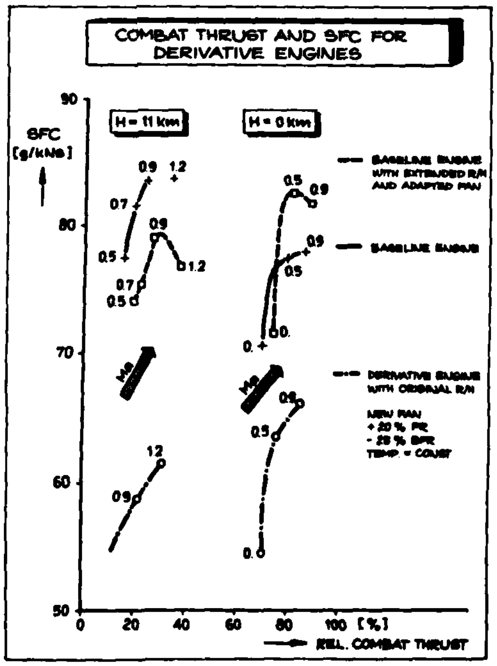
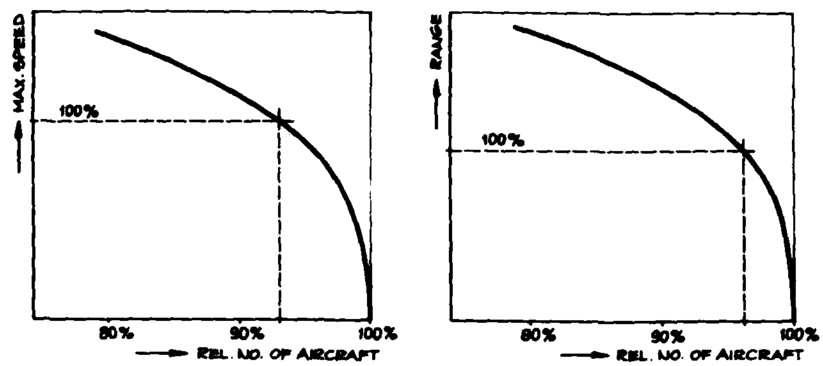


FIGURE 5

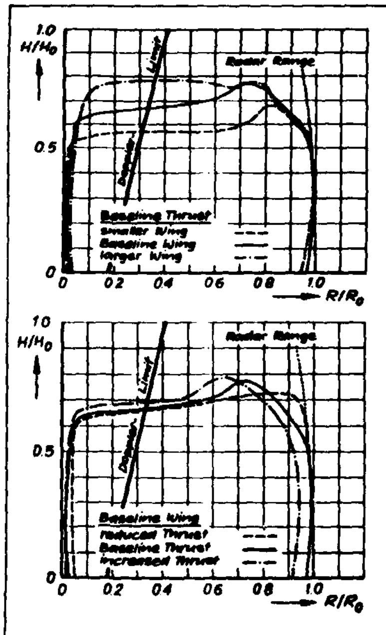
SCATTER OF FLIGHT PERFORMANCE



NORMAL DISTRIBUTIONS AROUND AVERAGE VALUES

a) THRUST	2.5 %	OF ENGINES WITH 2% LESS THAN AVERAGE THRUST
b) SFC	2.5 %	OF ENGINES WITH 1% HIGHER SFC THAN AVERAGE
c) DRAG	1.0 %	OF AIRCRAFT WITH 2% HIGHER DRAG THAN AVERAGE

FIGURE 6



MISSILE RANGE ENVELOPES

FIGURE 7

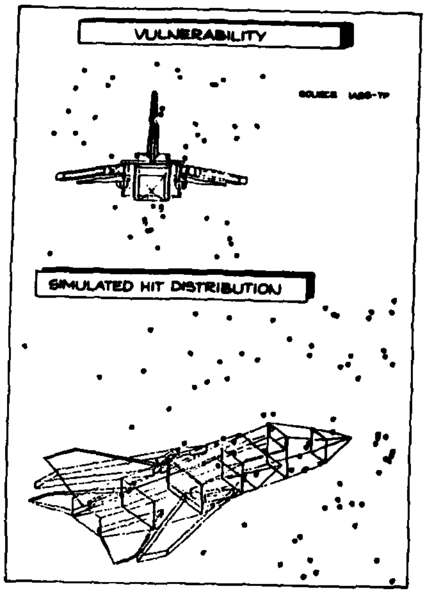


FIGURE 8

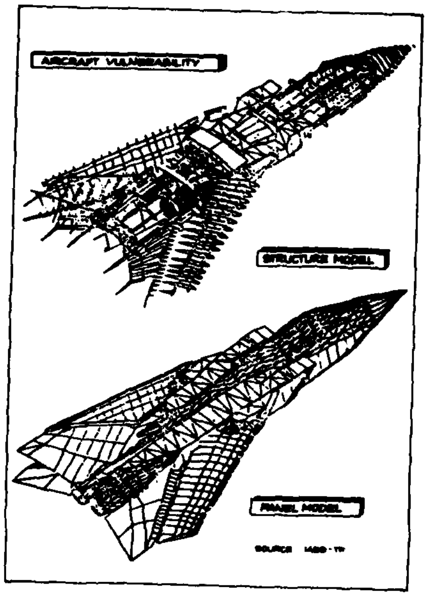
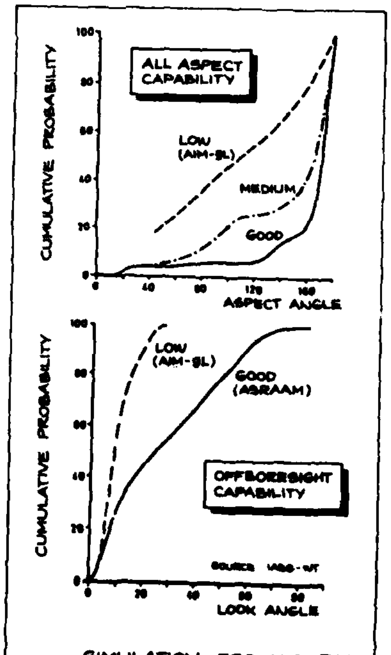


FIGURE 9



SIMULATION RESULTS FOR AIR-TO-AIR MISSILES

FIGURE 10

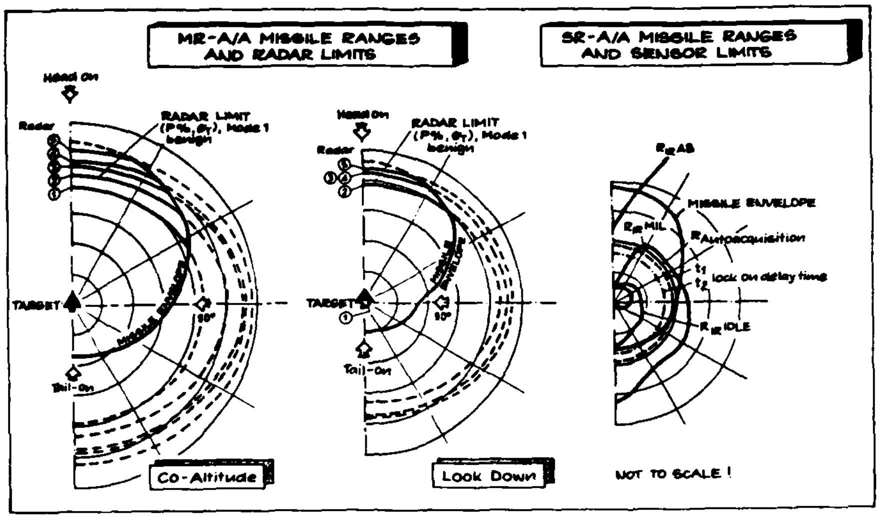
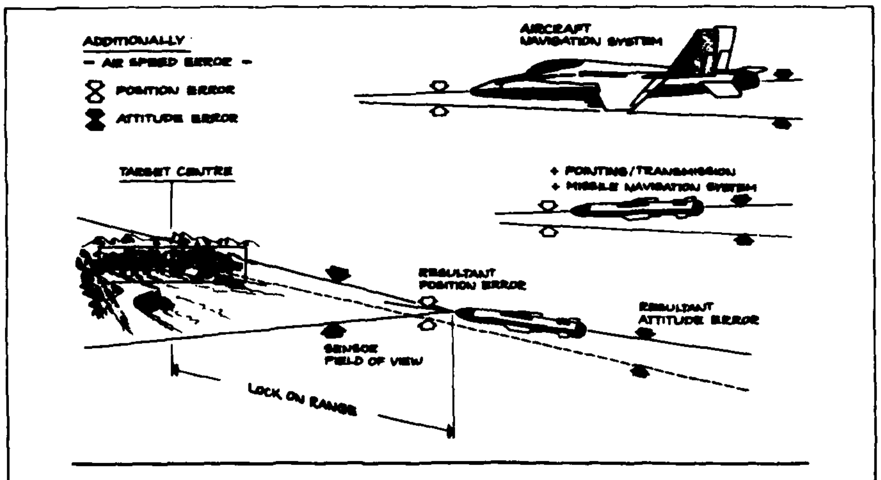


FIGURE 11



ERRORS IN MISSILE DEPLOYMENT

FIGURE 12

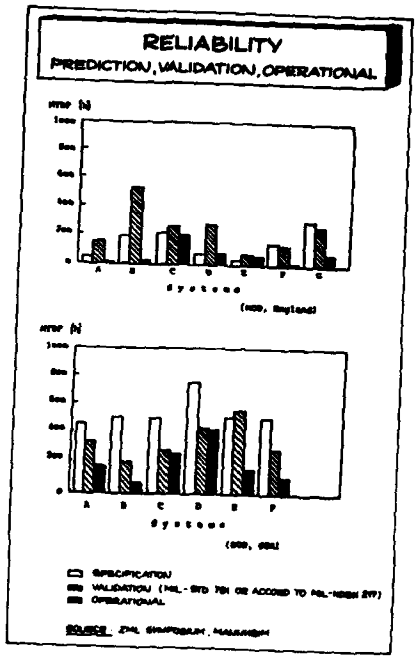


FIGURE 13

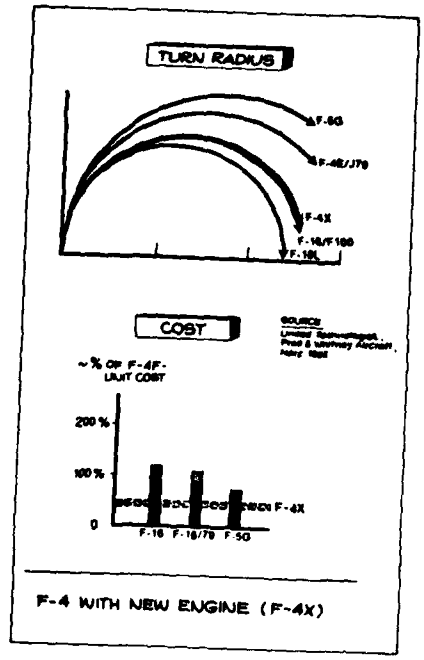
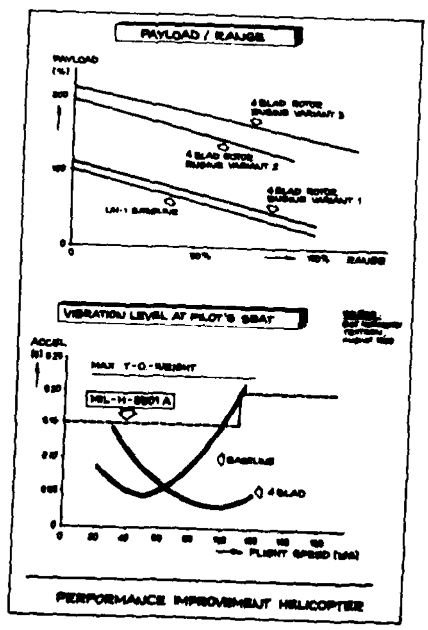


FIGURE 14



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SOME DEVELOPMENT TRENDS IN LIGHT GROUND ATTACK AIRCRAFT

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INTRODUCTION

The I.A.F. combat flight line is qualitatively and quantitatively determined by its institutional tasks and commitments undertaken by the country within NATO.
The operational requirements, that are continuously evolving, are derived from these tasks.
The national strategy stems from "Costituzione della Repubblica Italiana", in military terms, consist of the capacity to discourage the aggressive attitude of possible enemies and to defend the national territory, its air space and maritime lines of communication.
Within this strategy the I.A.F. tasks are the following:

- defend territory and supply routes from enemy's air raids;
- provide air support to surface force in defending national territory and keeping the maritime lines of communication open.

It is therefore necessary for the I.A.F., to have besides the weapon systems for air defense, interdiction, recce, and all weather interdiction strike, also aircrafts capable of:

- operating in the battle area and enemy's zone behind the front, providing recce and fire support to land forces;
- providing recce and fire support to naval forces in the Mediterranean area.

The national strategy is integrated in the NATO "flexible response" strategy that requires:

- conventional forces capable of discouraging possible attacks and driving them back by employing conventional weapons;
- weapons capable of dissuading the enemy from a possible employment of nuclear weapons, even if tactical, for fear of retaliation.

The I.A.F. operational requirements must be consistent with the national and NATO strategy concepts and, in particular, must take into account the content of the NATO doctrine accepted by Italy concerning the direction of air combat operations including those on support of land and naval operations (Fig. 1).
In the light of these national and NATO strategic concepts, the Italian Air Staff have initiated in 1970 a study with the aim of a rational modernization.
The study, brought forward with complex and up-to-date parametric methods, has indicated that the future I.A.F. combat flight line should consist of 3 major components:

(1) an "all weather interceptor" line on F 104/S whose armament, navigation and ECM systems are being modernized; from 1995 on, this A/C will be gradually replaced by the new EFA, now in definition;
(2) an "all weather recce/bomber attack" line on MRCA-Tornado, an A/C with high self-defence qualities;
(3) a "light bomber attack" line optimized for:

- close interdiction i.e. to cut-off the battle area, strike the second line forces and provide adeguate attack support to naval forces;
- reconnaissance as required for the fulfilment of close interdiction and close air support missions;
- close air support in the battle area by means of direct fire support.

Summarising, the study has shown that, while the "state of art" might provide a multirole A/C capable of coping with two or even all three roles, accepting three different components, would have been the most convenient solution in terms of cost/effectiveness.
This is the only way to obtain, at reasonable costs, the maximum effectiveness of the complete combat flight line.
In this context the AM-X programme finds its full justification.
On the basis of the role that the A/C is requested to satisfy and considering the financial possibilities of nations, by definition limited in front of requested defensive tasks, *the application of cost effectiveness criteria to the specific design requirement identification is again mandatory.*
The integration of the involved costs with the effectiveness evaluation over the complete mission in the most appropriate scenario, allows a more complete and significative evaluation in comparison with the analysis based on single phase effectiveness.
Moreover, the forecasting of the scenario where the weapon system is projected to be utilized, is difficult for the continuous and impetuous evolution of the scenario elements; therefore this approach is to be utilized to evidence the cost-effectiveness sensitivity to the possible threath evolution rather then to obtain definitive solutions.
The AM-X development, from specific design requirements definition up to the weapon system configurational characteristics identification, followed continuously this approach, allowing *to integrate sinergically requirements and operational experience* from DEFENCE with knowhow and information from INDUSTRY; all that, in a common effort and close cooperation.
In the next paragraphs, the driving effectiveness elements related to mission phases will be analysed, some significative cost-effectiveness results will be emphasized and the main characteristics of the AM-X will be illustrated in relation to previous considerations.

BACK GROUND OF IAF MODERNIZATION STUDY

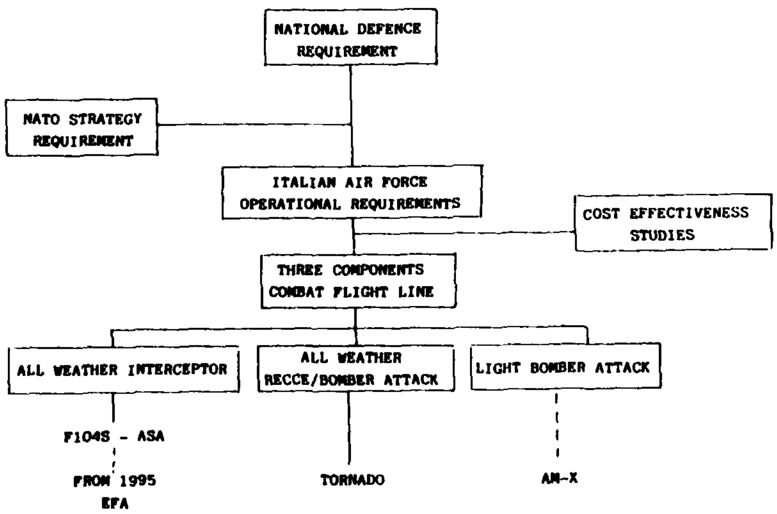


FIG. 1

SPECIFIC DESIGN REQUIREMENTS AND COST EFFECTIVENESS

The **operational requirements**, originated by considerations related to the air force strategy, define the role, the geographic area to be controlled and the warload capability of the requested weapon system. From these definitions it follows directly the specifications of mission profile and radius, the operative environmental limitations, the armament capabilities of the new air weapon system.
The general configuration characteristics of the airvehicle are originated from the **specific design requirements** directly related to the operational procedure that will be utilized in the forecast scenario. These requirements define flight performance for the different mission phases, define performance capabilities of the offensive and self defence armament systems, define the functionality target for the general systems of the aircraft.
These requirements represent one possible solution to the problem posed by operational requirements, and the cost-effectiveness approach is the basis to obtain the maximum effectiveness from a total cost acceptable for the nation economic capabilities.
The application of this approach is based on a model of mission effectiveness analysis and on a model of cost evaluation of weapon systems and its variants.
The implementation of realistic models is a very difficult task and their utilization is complicated by the uncertainties of the operative scenario forecasting.
In the AM-X programme the cost-effectiveness approach has been used with continuity but it has been applied basically to evaluate the sensitivities of cost-effectiveness to the possible variants of the requirements and, first of all, with the guarantee of a continuous exchange of information and results between DEFENCE and INDUSTRY.
How the cost-effectiveness approach has contributed to the specific design requirements definition is synthetically reviewed in the next paragraph.

MISSION EFFECTIVENESS ANALYSIS

The mission effectiveness model is based on the evaluation of the probabilities for each phase of the mission to overcome the threat or the task, to abort the mission and to loose the aircraft. The effectiveness is defined as the ratio of number of targets destroyed to number of lost aircrafts to do this task (Fig. 2).
The concept is extensible to a significative number of sorties.

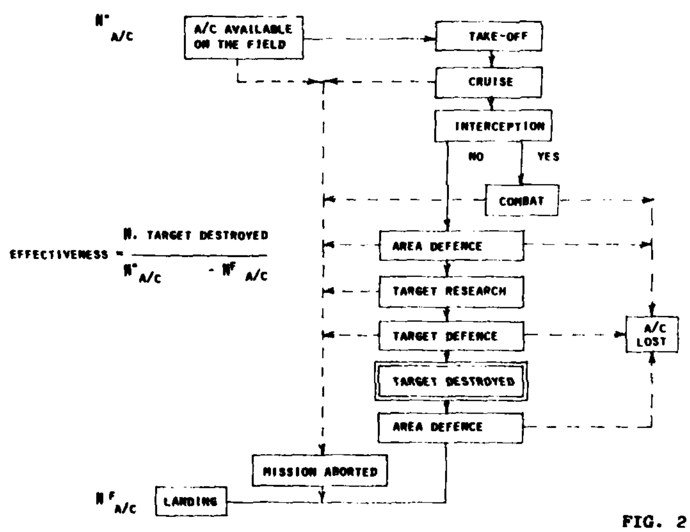


FIG. 2

For each phase of the mission, effectiveness factors have been identified and correlated with configurational and operating characteristics of the ground attack aircraft and with possible characteristics of the scenario (Fig. 3).

It is of interest to revisit these effectiveness factors in order to underline the more important ones and to evidence relations with configurational characteristis.

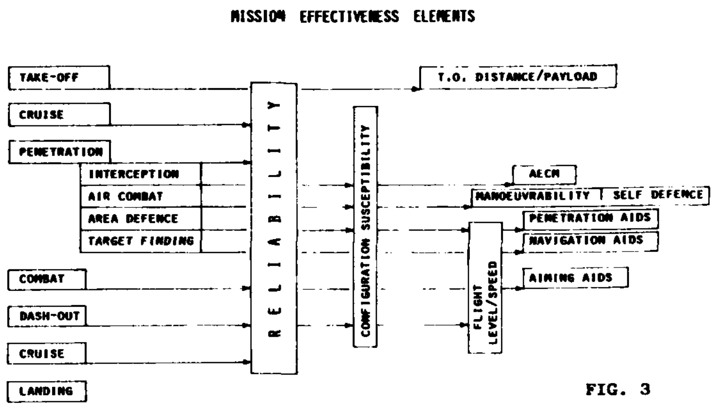


FIG. 3

The **system reliability** is a factor affecting all the length of the mission. Current modern combat aircraft have Mission Failure Rate (**MFR**) target to the order of 5×10^{-2}; it seems feasible for new projects to put a target MFR = 3×10^{-2} without affecting the system complexity.
This target is accomplished by a careful study of the redundancies and by a diligent monitoring, during design and development phases, of the basic reliability of each critical component. The redundancies will be simple (system lost after second failure) for systems assuring the mission performance, and will be with an emergency back-up for systems affecting the flight safety. Considering a typical distribution of reliability figures, obtainable applying previous concept (Fig.4), it's evident as avionics and electronic conditioned systems continue to be the main MFR producer.
For the propulsion, there is the long time argument about the single or twin engined aircraft.
From reliability point of view, it can be stated that, two engines have a defect rate higher than one engine; and considering that it is absolutely not cost-effective to install two engines, each one enabling the aircraft to maintain full performance, it results that the single engine A/C has a MFR lower than the twin engine A/C.

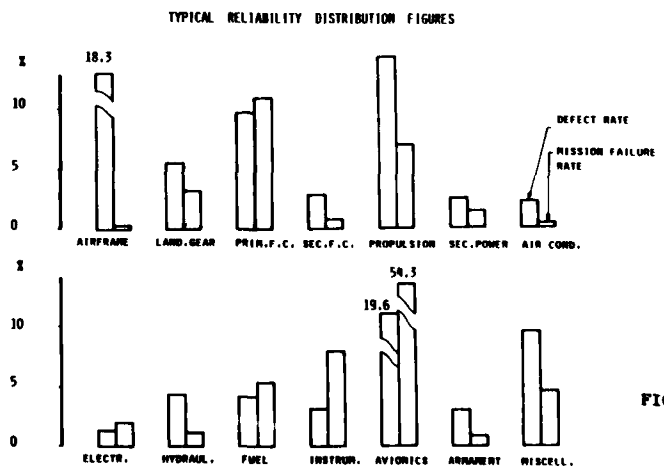


FIG. 4

The probability of interception is dependent from the enemy airforce deployment but, for what concern A/C characteristics, it depends from the susceptibility of the configuration.
The stealth technology was not yet mature to be considered as a specific design requirement, however the characteristics of visibility (smokes, camouflage and dimensions) and detectability to searching radar (**RCS**), had to be considered during the basic configuration definition.
Thus, it has been useful in cost-effectiveness analysis, to consider the interception probability as an indipendent variable, to be defined in accordance with scenario assumptions.
In any case when an intruder is intercepted, its mission must be considered aborted.
In effect for survivability, the intruder is forced to jettison external loads in order to gain its maximum potentiality to try to disengage from the dogfight.
In this phase of combat, the configurational characteristics of the airvehicle are of paramount importance: thrust/weight ratio, wing loading and lift boundary are the driving factors that determine the Probability to Survive in Combat.(**PSC**).
For the cost effectiveness analysis an empirical correlation between above parameters and the PSC has been established, based on results of a lot of combat simulations (Fig. 5, 6).
Basic assumption of this combat simulations was that the tactic of the intruder is to try to escape and that, at the beginning of the combat, no one of the contenders has an advantage position; in case that intruder is not warned of the interceptor presence, its PSC is dramatically reduced.
Considering the influence of airvehicle characteristics on PSC, it is very important to observe as attained manoeuvrability, related to wing loading and wing design for high lift boundary, has a beneficial influence on survivability.
Another important parameter that influences the PSC of the intruder is its IR Signature: the utilisation of a dry engine in respect to an engine with after-burner has on PSC an effect bigger than a thrust/weight ratio increase of 50%.
IRCM and ECM can reduce the probability to be hit by fired missiles and self defence weapons can reduce the firing opportunities of the interceptor.

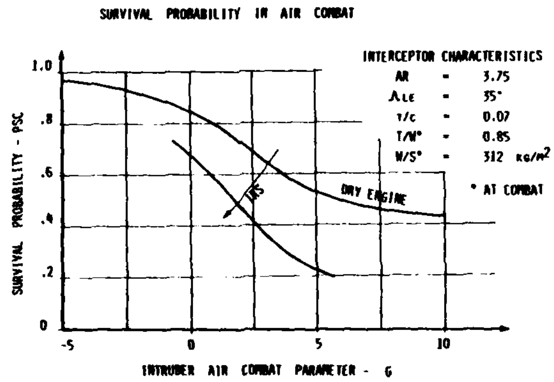


FIG. 5

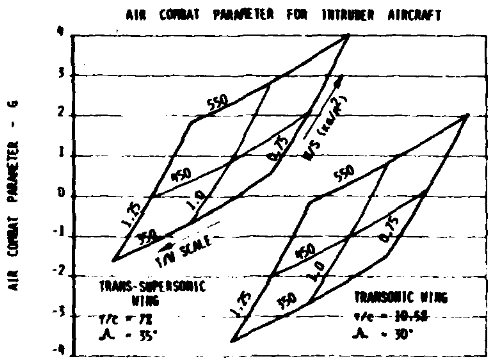


FIG. 6

During penetration intc enemy territory, the intruder has to face a deployment of AAA, based on optical and radar tracking systems, and Radar or IR guided SAMs.
The analysis of the survival probability during a penetration (**PSA**) over AAA defended territory, shows the great advantage of the ride altitude; the shot-down probability is reduced by 7 to 1 reducing the penetration altitude from 500 ft to 200 ft.
The Fig.7 shows the **PSA** evaluated against an AAA system based on optical tracking; it is evident that penetration speed is not more a critical factor only for very low level penetration.

SURVIVABILITY IN PENETRATION

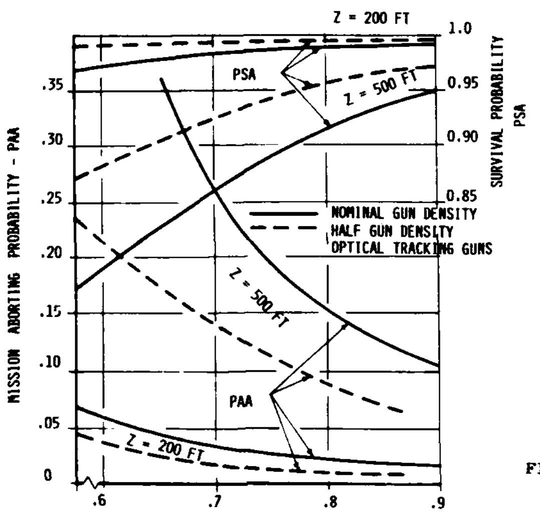


FIG. 7

The radar guided guns increase the shot-down probabilities in respect to the optical tracking guns, roughly of the same ratio 1 to 7, flying the intruder at the same altitude and speed; in this case it is essential to reduce the susceptibility of the configuration.
The effectiveness of penetration aids is not a easy figure but is a common knowledge that they can reduce this shotdown capability of the 70 - 90%.
On these basis, it is possible to consider the equivalence, in terms of survival probability in penetration, of the optical and radar tracking AAA systems, if the intruder is equipped with efficient penetration aids.
The target must be considered heavily defended, both by AAA and SAMs.
It is essential therefore to minimize the time spent over the target; as a consequence the navigation system and the aiming/release system performance are the effectiveness factors that determine the probability to find and destroy the target.
The probability to survive to SAM threat is related to the time of permanence over the target area and to the availability of effective defensive aids (AECM, chaff/flare, RW, IRM), automatically or continuously engaged.
From this survey of the main effectiveness elements during the mission, some first important indications emerge: penetration/defensive aids availability and IR signature of the engine produce changes in effectiveness of an order of magnitude higher than that of possible configurational variations. Therefore it is reasonable to specify in the design requirements the installation of penetration/defensive aids and the utilisation of a dry cold engine, without further examination of cost-effectiveness of such requirements.
The configurational characteristics that influence the effectiveness must be defined with the cost-effectiveness approach, considering in the scenario the above specified features.

To evaluate the cost-effectiveness it is necessary to implement a cost model that in a parametric way can give reasonable indication of the cost variation related to configurational parametric changes over a baseline.
Based on the historical RAND approach, updated for new data and technological innovation, the cost model works on data generated by a synthesis programme that scales airframe, engine and general systems of a baseline, in order to respect specified mission profile and specified configurational characteristics, like thrust to weight ratio, wing loading and aerodynamic wing characteristics.
In Fig. 8 the results of an exercise, applicable to our considerations, are reported; the costs normalized in respect to a baseline cost, are evaluated for two different wing design, a first one with a flight envelope limited at M = 0.9 (transonic wing), a second one with the flight envelope not limited at sonic speeds (trans-supersonic wing).

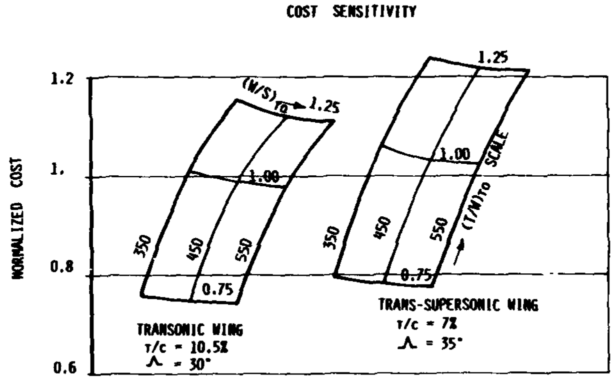
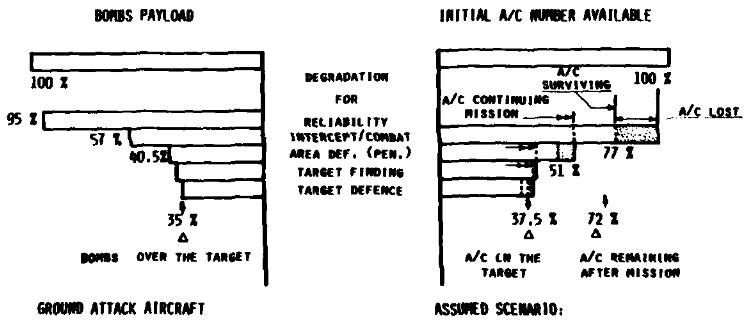


FIG. 8

EFFECTIVENESS AND COST-EFFECTIVENESS TRADES

In order to evidence the relative criticality of the different mission phases, the mission effectiveness analysis model has been applied to an existing light ground attack aircraft, stripped of all penetration/defensive aids, in a possible modern scenario.
The results (Fig.9), even if dependent from the scenario assumption, show realistically how dramatic can be the incidence of the interceptions and penetration phases.
Therefore concentrating the attention on these two phases, the effects on mission effectiveness of the configurational parameters (T/W and W/S) and of the main scenario parameters (Probability of Interception and Penetration Altitude) have been analysed.



GROUND ATTACK AIRCRAFT
$(W/S)_{TO}$ = 490 KG/M^2
T/W = 0.60

FIG. 9

ASSUMED SCENARIO:
PENETRATION DISTANCE/ALTITUDE ... NM/500 FT
INTERCEPTION PROBABILITY P_I = 0.4
AAA DENSITY 1 ZSU (23-4)/10 KM^2 (NOMINAL)
NO LOSSES DURING CRUISE BACK

In Fig.10, the two considered scenarios are characterized by the extreme criticality of the penetration phase. In this environment it is evident as the Thrust to Weight ratio is the driving configuration parameter even if the interception probability is increased. In effect the increase of T/W permits an higher penetration speed with a reduction of the shot-down probability.
Reducing the penetration altitude, the shot-down probability is greatly reduced and the mission effectiveness is accordingly increased. The case considered in Fig.11 is representative of a scenario where the incidence of air combat is predominant on the penetration phase risks; in this environment the positive influence of the increasing T/W ratio on the mission effectiveness is mantained, but also the reduction of wing loading shows a comparable effect. Two remarks are straight forward at this point.

- The mission effectiveness increases obtainable with the reduction of penetration altitude is considerably greater than the increases obtainable with reasonable configurational variants (T/W especially); therefore all the systems that permit to reduce the flyable penetration altitude or the susceptibility of the configuration, must be carefully considered;

- when the scenario is less demanding for penetration risks, the significant increase of mission effectiveness obtainable with the reduction of wing loading can be obtained also increasing the aerodynamic lift capabilities of the wing.

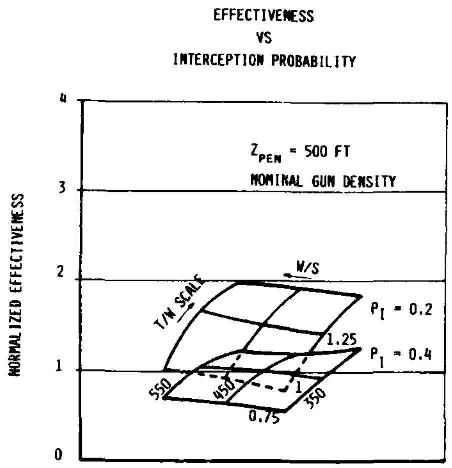


FIG. 10

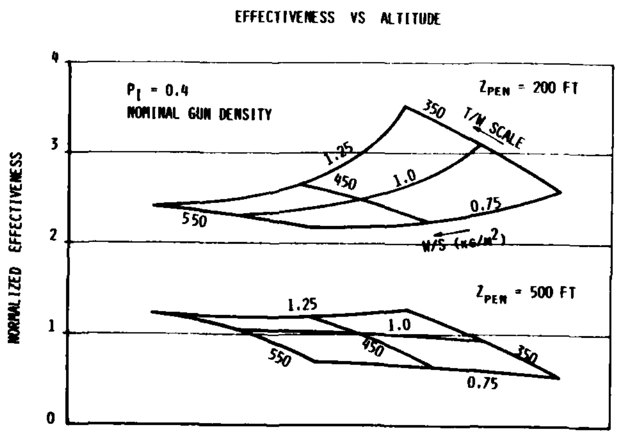


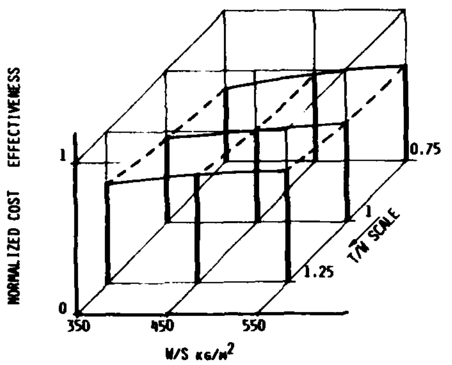
FIG. 11

Extending this analysis to the cost effectiveness aspects, the introduction of the cost factor reduces the influence of the Thrust to Weight ratio.

In the scenario dominated by the risks of the penetration phase the favourable effect of the increase of the T/W ratio is confirmed also in terms of cost effectiveness, as it can be seen in Fig.12, where the influence of T/W ratio and wing loading is evidenced.

In the scenario dominated by the probability of interception (Fig.13), the cost increase generated by higher T/W ratio highlights the importance of the low wing loading or, in comparable terms, of the high lift capabilities.

PARAMETRIC COST EFFECTIVENESS



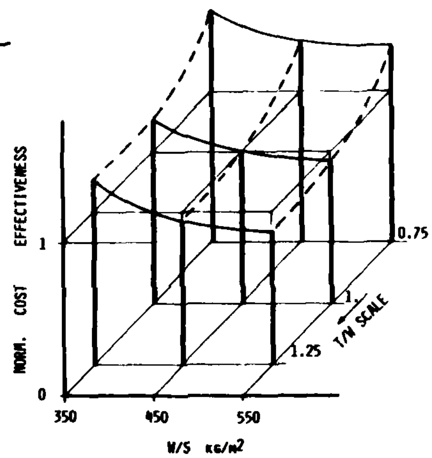
P_I = 0.2

Z_{PEN} = 500 FT

NOMINAL GUN DENSITY

FIG. 12

PARAMETRIC COST EFFECTIVENESS



P_I = 0.4

Z_{PEN} = 200 FT

NOMINAL GUN DENSITY

FIG. 13

This indication is confirmed also by the cost effectiveness analysis of the influence of the wing design, i.e. transonic or supersonic wing.

The lower cost and the higher lift capability of the transonic wing configuration give rise to a better cost effectiveness in both the scenarios.

COST EFFECTIVENESS SENSITIVITY

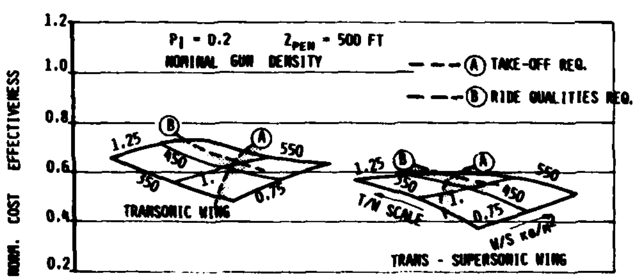


FIG. 14

Of course the advantage is limited in the scenario dominated by the penetration (Fig.14) when the interception is the conditioning factor of the scenario (Fig.15) the advantage in cost effectiveness can rise up to the 20%, at the same configurational conditions.

This advantage increases to the 25% if the comparison is made for conditions assuring same take off performance and same ride qualities.

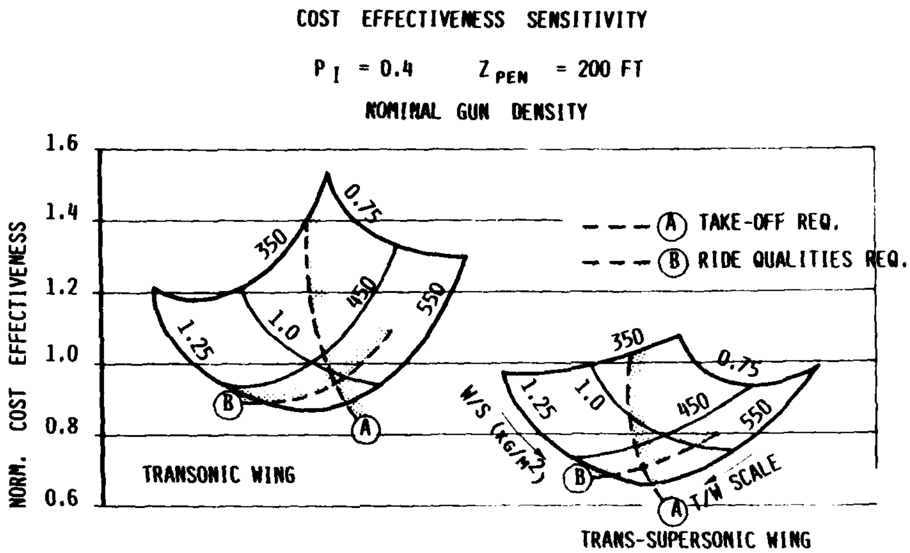


FIG. 15

Previous indications about cost-effectiveness sensitivities have been obtained in scenarios where the threat in penetration is based on optical tracking guns, but the general trend of sensitivities can be confirmed, considering the more deadly radar guided guns and SAMs.
With reference to previous consideration on survival probability in penetration phase, the presence of radar tracking guns in the scenario reduces the effectiveness of the low level penetration flight; practically, in this case, the scenario is dominated by the penetration phase also flying at typical 200 ft over the ground.
The installation on the aircraft of penetration/defensive aids and self defence armament can change the relative criticality of the two determinant mission phases, interception and penetration.
In fact Electronic and IR Counter Measures are particularly effective against radar and IR based threats. The estimation of the effectiveness of such devices is quite hard due to the continuous evolution of the offensive and defensive systems.
But assuming an optimistic attitude, justified by the present superiority of the counter measure devices, the reduction of hitting probability due to these devices can be expected up to 90%. In this case , if the penetration level is mantained at 200 ft, the scenario is again dominated by interception and air combat, and conclusions previously drawn for optical tracking systems are applicable.
The effectiveness of defensive aids (**AECM**) on interception probability is less evident. Untill the stealth technology at complete airframe level will be adeguately developed, the possibility to reduce the aircraft detectability from searching radars by means of active electronic counter measures, seems quite limited.
However defensive aids and self defence armament can influence favourably the survival probability in combat. Assuming an increase of survival probability of 50%, the mission effectiveness improvement results in about a 10% in a scenario dominated by interception phase. This low figure is a consequence of the assumed ineffectiveness of the AECM on interception probability.

In conclusion, the preceding considerations, also if exposed as examples of effectiveness and cost effectiveness critera applications, permit to identify some leading design requirements for a light ground attack aircraft capable to afford modern scenarios.
The electronic war devices are assuming a growing impact on the threat and on the aircraft armament systems
Presently and in the next future, the penetration phase, in particular, will be dominated by such devices and, among the configurational characteristics, only those permitting a very low level flight at speeds of about 470 - 500 KTS can be considered cost effective: adequate ride qualities, excellent pilot visibility and rational not task disturbing flight data presentation to the pilot, are the driving design features.
Due to the present inadequacy of the stealth technology to reduce significantly the interception probability, the configurational characteristics definition, that takes into account particularly the survival probability in combat, appears the most cost effective solution; for a light ground attack aircraft fighting against an interceptor the attained manoeuvrability performance and the low IRS in combat result more cost effective than the high escape speed.

FIG. 16: AM-X

AM-X - A DEDICATED ATTACK AIRCRAFT

According to the above considerations, the AMX (Fig. 16) has been designed to fulfill a well defined requirement for a modern, cost effective Weapon System with high flexibility and growth capabilities adequate to future more demanding operative needs, mainly in the avionic field, and to cover the main roles of:

- Close Interdiction to hit second line ground enemy forces and support friendly naval forces;
- Armed Reconaissance;
- Close Air Support of the ground forces in the battle area;

and in addition the secondary roles of:

- Offensive counter air against enemy airfield;
- Air Defence against low flying intruders in limited areas.

The basic requirements to accomplish such missions include (Fig. 17):

- good take-off and landing performances
- effective penetration capability with high military loads
- excellent low level flight behaviour
- high navigation and attack accuracy
- post failure operability
- penetration aids all embodied in a highly versatile weapon system

that, translated into technical requirements, means:

- high wing loading
- high lift wing
- low S.F.C. in Cruise and Dash speeds
- low vulnerability
- high reliability
- ease of maintenance
- high survivability
- good self protection

AM-X has been designed to fulfill all the above requirements.

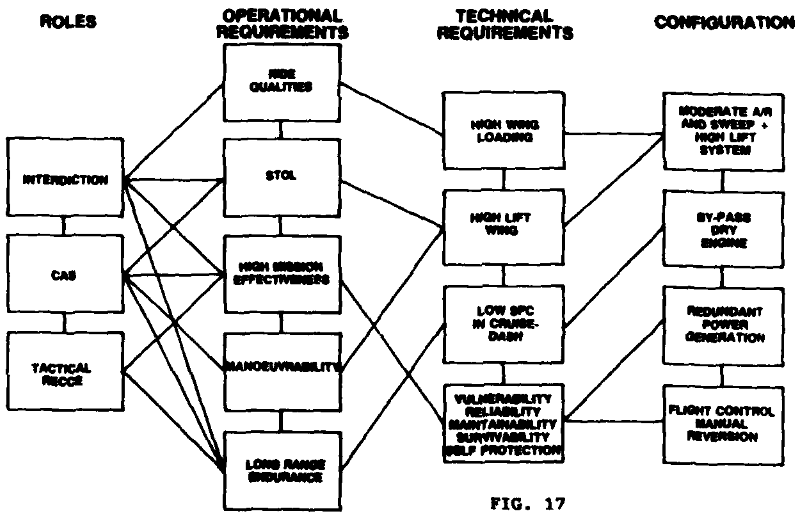


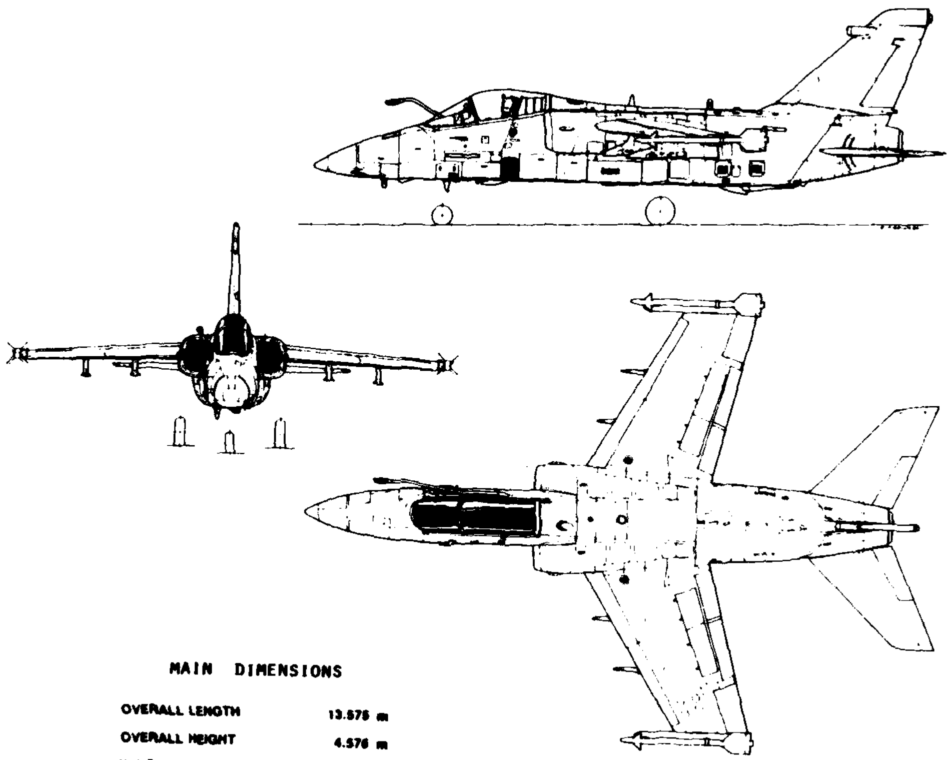
FIG. 17

DESIGN FOR MISSION SUCCESS

AM-X THREE VIEW

MASS BREACK-DOWN

OPERATIONAL EMPTY MASS	6700 kg
MAX TAKE-OFF MASS	12500 kg
MAX EXTERNAL LOAD	3800 kg



MAIN DIMENSIONS

OVERALL LENGTH	13.575 m
OVERALL HEIGHT	4.576 m
WING SPAN	8.874 m
WING AREA	21 m^2
ASPECT RATIO	3.750
WING SWEEP (25% c)	27.5°

FIG. 18

The AMX (Fig.18) is a single-seat, medium-high wing aircraft, powered by Rolls Royce SPEY MK 807 turbofan engine without afterburner.
Good payload radius and combat performance, penetration speed over 470 Kts at low altitude with good gust response and high stability during target tracking, lead to a well integrated weapon platform in relation with tasks and roles requested.

As a dedicated attack aircraft, AMX design has been centered around the fundamental features necessary to perform land or sea missions in a hostile environment with a high probability of success (Fig.19).
In addition features like readiness, low vulnerability, high survivability and safety are thus of prime importance.

DESIGNED FOR MISSION SUCCESS

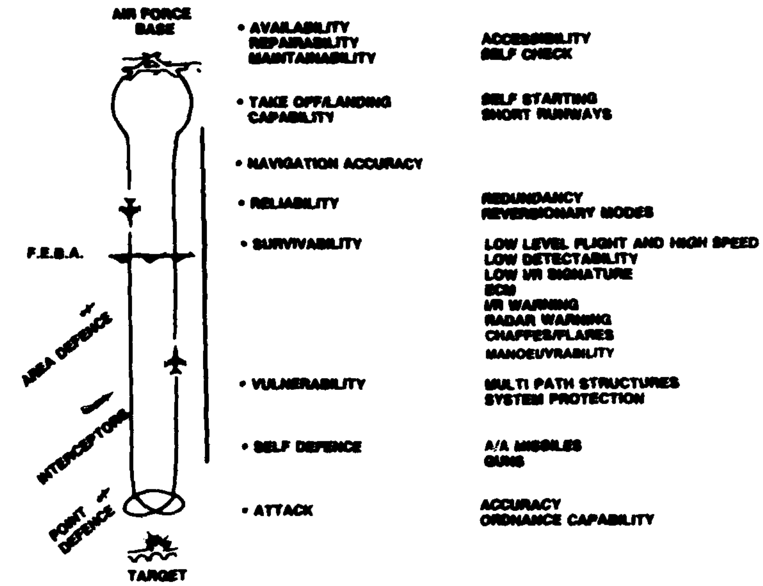


FIG. 19

Readiness has been enhanced on AMX making an extensive use of line replace e units and adopting the "on condition" maintenance concept.
Built-in test and monitoring systems are integrated, whenever possible, while failure information is recorded and displayed on a ground crew accessible Central Maintenance Panel.
Systems and components are easily accessible to reduce both turn-around time and line maintenance operations. Inspections may be made through more than 200 access panels and doors.
Pre-flight checks may be accomplished in 10 minutes (one man) as well as turn around time (two men).
Mission readiness is also provided by a Secondary Power System (APU) for self starting capability and continuous air conditioning and essential electrical power for operation from poorly equipped bases, while take off and landing capabilities allow to operate from partially damaged runways.

High mission **reliability** and low **vulnerability** are enhanced on AMX by the fact that all systems are designed to assure the successful completion of the mission following a first failure to a major system and the safe return to base even after a second failure.

- Redundant and separated Flight Control, Hydraulic, Electrical, and Avionic systems allow mission completion after first hit.

- Manual back-up for flight controls and emergency capability on onboard battery allow a safe return to base after a second failure.

In addition protection of critical components is also assured by the shielding effect of non-essential equipments or through a battle damage tolerant structure.

The AMX design emphasizes on **survivability** aspects achieved by means of excellent low level flight behaviour (speed and manoeuvrability) associated with:

- reduced radar equivalent cross section
- low infrared signature
- low noise level
- small dimension and camouflage
- highly integrated self protection system (Active and Passive ECM, Chaff and Flares, Radar Warning, Missile Launch and Approach Warning)
- self defence capabilities (A/A Missiles and Guns).

Attack accuracy achieved by the use of a dual-channel computerized system for release or launching of weapons along with the installation capacity, at seven hard points, for a wide range of ordnance (Fig.20), enables formidable battlefield interdiction and close air support roles.
The fuselage has also space provision for the installation of different types of radar if required for specific roles.
For reconnaissance missions three interchangeable pallet mounted photographic systems (panoramic, TV and photogrammetric) can be internally carried, while an external infrared/optronics pod can be mounted on the centerline station.

Avionics is one of the major elements in mission success and AMX has a full avionic configuration (Fig.21) covering about 10% of Operational Mass Empty.
The **Navigation/Attack** system is centered around two main computers connected to the various sensors and displays via a digital data bus which assures maximum accuracy with minimum pilot workload.
The system has been designed in term of redundancy and selftest monitoring to permit successful mission completion in the event of a failure in the flight management system and the safe return to base even after a second failure.
In addition the modular design and digital data bus allow new systems, currently undergoing development, to be readily integrated; for example new NATO identification and data transmission systems JTIDS and NIS, GPS/NAVSTAR for precise navigation and even MLS can be quickly installed without affecting existing functions (Fig.22).
All avionic equipment packages are ergonomically positioned to allow rapid access for routine maintenance and configuration changes.

A two seat version of the AMX is envisaged for operational conversion unit and advanced training for pilots and system operators.
High commonality between the single and two-seat version will be maintained, including all the operational systems, facilitating the simultaneous operation of both variants on the same flight line without the requirement for additional AGE.

FIG. 20

EXTERNAL ARMAMENT

THE AMX CAN CARRY A MIX OF THE FOLLOWING WEAPON TYPES WITHIN THE 7 HARD POINTS SPECIFIED LIMITS:

- **BOMBS (FREE FALL OR RETARDED) MK 82 - MK 83 - MK 84**
- **ROCKETS**
- **CLUSTER BOMBS**
- **STAND-OFF WEAPONS DISPENSER**
- **PRECISION GUIDED MUNITIONS (ELECTRO OPTICAL GUIDE)**
- **AIR-TO-GROUND MISSILES**
- **ANTI-RADIATION MISSILES**
- **ANTI-SHIP MISSILES (RADAR AND ELECTRO OPTICAL GUIDE)**
- **SHORT RANGE AIR-TO-AIR MISSILES**

MAX EXTERNAL LOAD AT NOMINAL ERU CAPABILITY 8500 lbs

AVIONIC SYSTEM

COMMUNICATION, IDENTIFICATION	UHF, VHF, CSU INTERCOM, VOICE RECORDER IFF/CRIPTO COMPUTER NIS, JTIDS (SPACE PROVISION)
NAVIGATION	INS, SAHRS, TACAN, VOR/ILS ADC, RADAR ALTIMETER NAVSTAR/GPS, MLS (SPACE-PROVISION)
COMPUTING	NAVIGATION/ATTACK COMPUTERS
FIRE CONTROL	HUD, RANGING RADAR, A/S RADAR, LASER STORE MANAGEMENT SYSTEM TV & IR DISPLAY
PENETRATIONS AIDS	ECM, CHAFFES, FLARES MISSILE LAUNCH/APPROACH WARNING RADAR WARNING
RECCE SYSTEM	3 DIFFERENT INTERNAL PALLETS AND IR RECCE POD

FIG. 21

AVIONICS AND ARMAMENT SYSTEM INTEGRATION

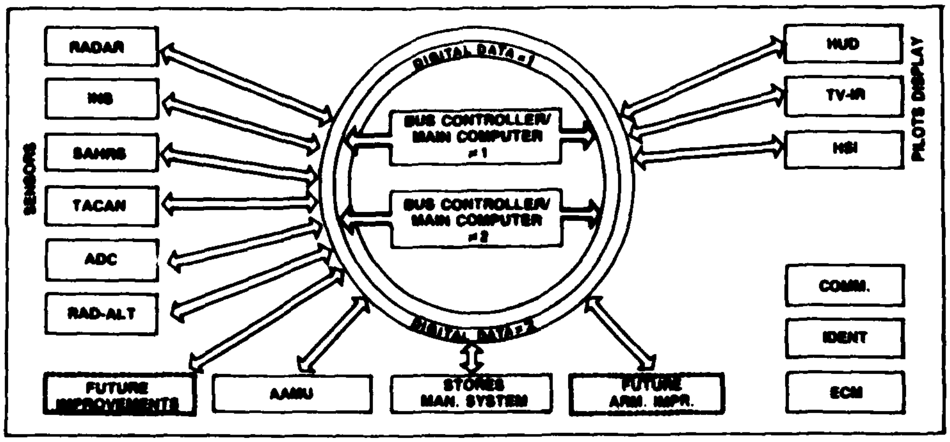


FIG. 22

POLYVALENCE DES SYSTEMES D'ARMES :
Un défi économique et opérationnel

par
le Colonel Jean-Jacques FLOCH
Division NOUVEAUX AVIONS DE COMBAT DE L'Etat-major de l'armée de l'air
(FRANCE)

Avec l'élargissement du concept de système d'armes, l'exécution des missions aériennes conduira l'avion de combat des années 90 à rencontrer, au cours d'une même mission, des phases de vol durant lesquelles ses capacités air-air et air-sol seront alternativement voire simultanément mises à l'épreuve.

Cette nouvelle notion de polyvalence doit être prise en compte dans la définition de l'avion et en particulier dans celle de son système d'armes.

Le concept d'avion de combat polyvalent a fait l'objet de nombreux débats au cours des dernières années et compte probablement autant de partisans que de détracteurs.

L'application des nouvelles technologies, en particulier celles issues de l'informatique, à la conception et à la réalisation des appareils et de leur système d'armes conduit toutefois à réviser la notion traditionnelle de polyvalence.

En effet, avec l'élargissement des capacités opérationnelles de chaque vecteur et du système d'armes global auquel il appartient, la polyvalence requise devient avant tout une capacité à remplir chaque mission dans un environnement opérationnel toujours plus complexe et très évolutif.

Cette faculté d'adapter les capacités de l'avion de combat à l'évolution du besoin opérationnel dans le temps s'accompagne d'exigences liées aux contraintes économiques. En effet, l'accroissement des coûts des matériels modernes dépassant celui des budgets disponibles, le nombre d'avions acquis en est réduit. L'efficacité globale des forces aériennes passe donc de plus en plus par la recherche du meilleur compromis entre les performances et le nombre d'appareils soit, en d'autres termes, par la capacité de chaque appareil à remplir la plus grande variété de missions.

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* *

Un avion est traditionnellement considéré comme polyvalent lorsqu'il peut équiper indifféremment des unités de défense aérienne ou d'appui tactique.

Le concept de polyvalence n'implique donc pas nécessairement une polyvalence des équipages. Celle-ci n'est requise que dans le cas où l'unité concernée se voit attribuer deux missions de nature différente, l'une d'elles étant, en l'occurence, classée mission principale marquant ainsi une priorité dans l'entraînement et la qualification des équipages.

Quant à l'avion, la logique voudrait que ses performances opérationnelles soient d'autant meilleures que l'on est parvenu à l'optimiser pour sa mission de base, ce qui tendrait à exclure la polyvalence. L'histoire nous montre pourtant que les avions les mieux réussis comme le PHANTOM et le MIRAGE III E possédaient une certaine polyvalence, ou plus exactement une efficacité acceptable dans un large éventail de missions.

L'acceptation de ce compromis au niveau de l'efficacité s'accompagne par ailleurs d'avantages significatifs : Ainsi, la capacité d'un avion à remplir une grande variété de missions donc à équiper un plus grand nombre d'unités élargit sa production et réduit proportionnellement le coût unitaire de la série.

La souplesse d'emploi et l'interopérabilité sont également des avantages essentiels de la polyvalence : leur importance est d'autant plus grande que les ressources et les moyens de l'Armée de l'air utilisatrice sont modestes.

La souplesse d'emploi se traduit par une possibilité de basculement de l'ensemble des forces aériennes dans l'exécution de la mission qu'impose la situation du moment. L'interopérabilité quant à elle élargit les possibilités d'action dans le cadre d'une alliance. L'une et l'autre ont des retombées logistiques fondamentales car elles permettent une rationalisation de la gestion, une simplification des procédures et une réduction des coûts relatifs aux volants, aux rechanges et aux matériels optionnels.

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Malgré ces avantages, certaines exigences opérationnelles contradictoires ont fait obstacle à la réalisation d'un appareil véritablement polyvalent.

Il s'agit, pour la cellule, de satisfaire les exigences liées aux performances supersoniques et au besoin d'agilité à toutes altitudes dans la plus grande plage de vitesse, tout en conservant la stabilité requise pour le vol à très basse altitude.

Le moteur doit, quant à lui, répondre aux exigences les plus contradictoires puisque son cycle de fonctionnement doit à la fois respecter les contraintes liées aux performances d'accélération supersonique, au combat air-air à toutes altitudes, et celles associées à la performance de décollage en charges lourdes et à la recherche d'un rayon d'action maximum à basse altitude pour la mission de pénétration lointaine en croisière transsonique (Cs faible).

Le système d'armes enfin, doit offrir le maximum de capacités tous temps dans les différents modes de fonctionnement et les capacités de tir d'une vaste panoplie d'armements avec la précision requise par l'efficacité des charges militaires. Ceci implique une adaptation des différents capteurs embarqués et particulièrement du radar, considéré jusqu'à présent comme le capteur principal du système de navigation et d'armement. Les différences considérables existant entre les cibles air-air et les objectifs air-sol, tant sur le plan des caractéristiques que sur celui de l'environnement, sont l'une des principales difficultés à résoudre pour l'obtention de cette polyvalence. Les performances requises du système d'armes sont en effet imposées à la fois par la nature de l'objectif à détruire et par l'efficacité estimée des divers armements.

La diversité des objectifs et l'évolution de leur nature dans le temps rendent de surcroît difficile l'obtention d'un compromis fondé sur des solutions techniques simples : une véritable polyvalence nécessite donc une constante adaptation du système et de fréquentes remises à niveau. Elle entraîne un inévitable accroissement de la complexité, élément fréquemment mis en relief par les détracteurs de la polyvalence. Une complexité accrue se traduit souvent en effet par un accroissement de la masse, donc du coût. Les gains apportés par l'économie d'échelle sont évidemment tempérés si le coût de la polyvalence s'accroît.

Jusqu'à présent, le concept traditionnel de polyvalence se heurtait donc à des exigences opérationnelles contradictoires que ne pouvaient satisfaire simultanément les choix techniques imposés. L'accélération de l'évolution technologique à laquelle nous assistons depuis 10 ans permet d'entrevoir de nouvelles solutions au problème posé. Les retombées opérationnelles qu'elle engendre nous contraignent en revanche à reconsidérer les conditions d'exécution des missions dont l'analyse aboutit à une nouvelle notion de polyvalence.

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Les commandes de vol électriques sont l'exemple le plus couramment cité de solution technique au problème de la polyvalence. Elles satisfont en effet le compromis agilité - stabilité en offrant une maniabilité exceptionnelle et une sécurité accrue tout en gommant l'effet des charges externes. Elles conduisent surtout au contrôle automatique généralisé (CAG ou CCV) qui représente le pas décisif vers une véritable polyvalence de la cellule et que concrétise l'aile à cambrure variable (M.A.W). La réduction de masse par l'utilisation généralisée de matériaux composites participe également à cet accroissement de la polyvalence. En effet, à masse égale, la capacité d'emport d'équipements et d'armements se développe, de même que s'améliorent les performances.

Pour le moteur, l'adoption d'un cycle variable permettant d'adapter les performances en fonction du type de mission sera, à terme, une solution satisfaisante. Dans l'attente, une régulation numérique permettant d'intégrer véritablement le moteur en le rendant accessible aux exigences opérationnelles élaborées par le système d'armes est une amélioration concrète en faveur de l'adaptation du moteur aux exigences des différentes missions.

Mais c'est dans le domaine de l'électronique et des techniques numériques que les nouvelles technologies apportent les capacités les plus spectaculaires. C'est par conséquent la conception du système d'armes et la qualité de son intégration qui permettront de satisfaire efficacement le besoin de polyvalence. Il importe qu'il le soit car ce besoin s'accentuera à mesure que les forces adverses développeront elles aussi ces techniques et qu'elles élargiront leur domaine d'action.

Cet élargissement des capacités opérationnelles procède en premier lieu de la nouvelle dimension à donner au concept de système d'armes. Compte tenu de la nécessité opérationnelle fondamentale de connaître l'environnement et compte tenu du besoin concomitant d'intégrer de plus en plus étroitement les sources de renseignements et les capteurs, un système d'armes ne peut plus se limiter aux équipements contenus dans la cellule d'un avion de combat. En fait, du satellite permettant la localisation du porteur, à la munition que l'on guide vers la cible à partir des données avion, sans oublier l'avion de détection lointaine qui détecte, localise et évalue les menaces potentielles, la synergie de chaque maillon de cette chaîne est renforcée par la transmission d'ordres et de données reliant chaque élément de ce système d'armes considéré comme un tout.

Ce nouveau concept de système élargi conduit à la notion d'ensemble de fonctions opérationnelles visant à délivrer des armements sur des objectifs localisés et identifiés avec précision. A ce titre, la fonction opérationnelle correspondant à l'acquisition de la cible prend en compte l'ensemble des capteurs inertiels, électromagnétiques, infrarouges sans négliger l'oeil et le cerveau du pilote, dont l'efficacité devra de plus en plus être évaluée en terme de capacité de gestion du système plus qu'en adresse à piloter la plateforme. Il en découle aussi que la sophistication dans la recherche des performances doit être transférée de l'avion en tant que porteur au système d'armes pris dans son ensemble. La notion de polyvalence prend alors à l'évidence une toute autre dimension. En raison, tout d'abord du fait que ce nouveau concept de système d'armes est également pris en compte par les forces adverses.

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Les conditions d'exécution des missions vont probablement évoluer avec l'exploitation de plus en plus poussée de technologies nouvelles. Le domaine d'utilisation des systèmes d'armes s'élargira, particulièrement à très basse altitude, de jour comme de nuit et quelles que soient les conditions météorologiques. La diversification des moyens offensifs et défensifs ainsi que l'accroissement des capacités à les coordonner engendrent inexorablement un environnement opérationnel de plus en plus sévère, complexe et difficile à appréhender par le pilote. Que l'engagement des forces aériennes soit orienté vers la nécessité de contrer un volume important d'attaques prononcées essentiellement à basse altitude ou vers la tentative de réduire le potentiel ennemi par la destruction au sol de ses moyens aériens, de ses installations ou de ses forces terrestres, la polyvalence des avions disponibles restera un atout précieux. Mais l'exécution de chaque type de mission implique en elle même une polyvalence car, quelle que soit la mission réalisée, l'avion de combat des années 90 rencontrera des phases de vol durant lesquelles ses capacités air-air ou air-sol seront alternativement voire simultanément mises à l'épreuve.

A titre d'exemple, une mission de défense aérienne contre des raids pénétrant à basse altitude ne peut, malgré les capacités "look down shoot down" des avions modernes, s'envisager sans une capacité à suivre le terrain au plus près quelles que soient les conditions météorologiques : cette capacité est indispensable à la fois pour poursuivre une cible évasive et pour se soustraire à une riposte éventuelle ou aux coups des défenses sol-air adverses. La diversité des moyens de détection, la dilution des menaces dans l'espace et les performances des armements confondent de plus en plus le chasseur et la cible accélérant ainsi l'alternance des phases offensives et défensives.

De la même manière, une mission de pénétration ne peut s'envisager à terme sans une capacité à prendre en compte les menaces air-air susceptibles de compromettre l'exécution de cette mission. Si le tir des armements d'autodéfense n'est pas le but de la mission, l'incapacité de l'exécuter au moment crucial risque d'en compromettre l'issue. En tout état de cause, une bonne évaluation de la menace est la meilleure garantie d'une prise de décision adaptée, au bon moment.

Ces exigences représentent une nouvelle forme de polyvalence au niveau du système d'armes : celle qui permet de gérer les différents capteurs et de traiter les données correspondantes, simultanément dans différents modes de fonctionnement, considérés jusqu'à présent comme spécifiques de missions air-air ou air-sol. Une telle capacité implique l'adoption de technologies telles que celles des circuits intégrés très grande vitesse, du balayage radar électronique, et de la transmission de données à grand débit. Elle représente un inévitable accroissement du coût global des systèmes qui, compte tenu des contraintes budgétaires prévisibles, risque de limiter le nombre d'appareils dont pourront disposer les forces. Elle engendre donc pour ces appareils une nécessité accrue de pouvoir effectuer l'éventail des missions confiées à ces forces.

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Pour résoudre le problème ainsi posé il faut donc orienter la conception de l'avion de combat polyvalent vers un compromis permettant :

- de répondre aux performances requises par les conditions d'exécution des différentes missions ;
- d'intégrer l'appareil dans un concept élargi de système d'armes, tel qu'il a été précédemment évoqué ;
- de préserver une évolution ultérieure engendrée par l'apparition de nouvelles techniques ou la modification des exigences opérationnelles ;
- de répondre à différents niveaux de spécifications opérationnelles prenant en compte des contraintes financières temporaires ou adaptées aux contingences économiques.

La première orientation, concernant le respect des performances requises, conduit à concevoir un système d'armes polyvalent dans un porteur satisfaisant l'essentiel des performances en air-air mais prenant en compte les capacités d'emport exigées par les missions air-sol.

La polyvalence du système d'armes peut être envisagée à différents niveaux :

Niveau 1 Une polyvalence totale se traduisant par la capacité de chaque appareil à effectuer tous les types de mission en emportant indifféremment d'un vol à l'autre des armements air-air ou air-sol et en s'intégrant à la demande à un réseau d'informations tactiques. Elle implique bien entendu la capacité multifonctions permettant la simultanéité de fonctionnement du système en mode air-air et air-sol quand les phases de la mission l'exigent.

Niveau 2 Une polyvalence optionnelle impliquant une reconfiguration de l'avion pour l'adapter à un type donné de mission. Cette reconfiguration consiste à adapter les capteurs associés aux armements et éventuellement à charger le logiciel correspondant. C'est la polyvalence qui permet de basculer en quelques heures une unité complète d'une mission à une autre en fonction des impératifs opérationnels. Toutefois, quel que soit le type de mission choisi, le système conserve la polyvalence minimale permettant à l'avion isolé de faire face à l'alternance des phases offensives et défensives qui caractérise leur exécution.

Niveau 3 Une polyvalence modulable permettant, au sein d'une même unité, d'affecter à chaque appareil les capteurs correspondant à sa spécialisation du moment.

Dans cette hypothèse, la polyvalence n'existe qu'au niveau de l'unité ou de patrouilles constituées au sein desquelles chaque appareil joue un rôle particulier. C'est le concept de système d'armes de patrouille qui permet à l'évidence de construire un avion plus léger, donc moins cher, mais qui pose un problème important de gestion des moyens (avions, capteurs et armements) au niveau de l'unité.

Quel que soit le niveau de polyvalence choisi ou imposé par les contraintes budgétaires, un certain nombre de principes doit être respecté dans la conception du système d'armes.

Il importe en premier lieu de concevoir un système de base se caractérisant par une grande aptitude à recevoir un nombre variable d'équipements et de capteurs différents. Dans le cadre d'une coopération cette souplesse doit couvrir l'éventail des diverses fabrications et options nationales.

Cette capacité implique la plus grande modularité dans la conception des logiciels et une architecture confiant aux capteurs le traitement primaire des signaux.

Il faut d'autre part prendre en compte dès la conception,les évolutions ultérieures qu'offrira l'évolution des techniques et, partant d'une polyvalence éventuellement réduite, conserver au système les capacités d'atteindre ultérieurement la polyvalence de niveau 1 qui reste l'objectif à atteindre.

Il faut enfin préserver les deux avantages majeurs de la polyvalence : la souplesse d'emploi et l'interopérabilité.

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En conclusion, il apparaît que la notion traditionnelle de polyvalence a fait place pour l'avion de combat moderne, à la capacité de s'adapter à l'évolution de l'environnement opérationnel. Si les avantages opérationnels de la polyvalence sont plus que jamais d'actualité, des solutions techniques nouvelles permettent d'atteindre un compromis satisfaisant.

En effet, ce sont les performances du système d'armes, pris dans son concept le plus large ainsi que son potentiel d'adaptation et d'évolution qui offrent à l'avion de combat des années 90 l'*essentiel de sa polyvalence*. C'est au stade de la conception que la souplesse de ce système doit être prise en compte afin de préserver l'avenir et de favoriser la coopération en permettant à chaque pays d'adapter son outil de défense à ses moyens et à ses exigences opérationnelles spécifiques.

AD-P005 614

EVOLUTION OF COMBAT PERFORMANCE OF THE HAWK LIGHT COMBAT AIRCRAFT

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SUMMARY

The paper reviews the progressive evolution of the BAe Hawk from its original concept as the advanced flying trainer aircraft for the RAF to the currently planned developments as a light attack aircraft. The developments are described in aerodynamics propulsion and systems to give improvement in performance and weapon delivery capability appropriate to effective light attack operational roles.

1. INTRODUCTION

The Hawk concept originated from the decision in the 1970's for the RAF to reorganise its flying training from the previous multi-aircraft system to a more integrated system in which advanced training could be accomplished on a single aircraft capable of taking the trainee pilot from the basic level to advanced flying training, weapon training and on to operational training.

In parallel with this RAF concept of integrated training the Hawk was also conceived in design as capable of development towards a light attack aircraft. These developments from the two-seat training version were through systems, performance and weapon capability developments, within controlled cost targets suited to potential market opportunities and local defence requirements.

2. DEVELOPMENT OVERVIEW

The original Hawk to meet RAF requirements, designated T Mk.1, was developed to a limited operational capability with Air-Air and Ground Attack weapons, as a secondary light attack aircraft, T Mk.1A.

The first export development was to meet a requirement for an advanced training and ground attack aircraft, accomplished by the development of additional weapon carriage and associated systems, designated the Mk.50 series.

This theme of development for the dual role of flying training and combat capability was taken further with additional weapon and system capability, performance improvements and uprated engine, embodied in the Mk.60 series.

Further development was seen on the basis of the developed airframe, for the roles of advanced systems and crew training and of a light attack aircraft. In the first of these developments, the Mk.100 series, enhanced ground attack capability is introduced through improved avionic systems giving self-contained navigation to targets, greater attack accuracy, versatile programable displays and a database system to give future system development capability.

The development to a single-seat version of the aircraft had been seen as a logical step to a full operational light strike aircraft in which the development capability in aerodynamics, performance, systems and sensors would be justifiable.

This development, the Mk.200 series, is again on the basis of the original airframe, but changing the front of the fuselage to new equipment and cockpit modules. By this means equipment and weapon system configurations for a range of operational roles are available and include:

* Night/All weather intercept from airborne alert
* Close support
* Interdiction
* Reconnaissance
* Maritime strike.

The enhancement of systems and performance, coupled with role capability and low visibility make the Series 200 an effective low cost light attack aircraft.

3. CURRENT STATUS OF THE HAWK DEVELOPMENT PROGRAMME

The T Mk.1 is currently in service with the RAF and has achieved a total of 287,500 flying hours.

A number of the T Mk.1 aircraft have been converted to T Mk.1A standard and are operational.

The Mk.50 series is in service with 3 other air forces.

The Mk.60 series is in service with a further 4 air forces.

The Mk.100 series is in the development stage through avionic systems ground rigs and will reach a flight development stage in 1987.

The Mk.200 series has been designed initially as a demonstration and development aircraft and will fly in this role in May 1986 with further plans to fly specific equipment development versions in 1987.

4. EVOLUTION OF COMBAT DEVELOPMENT

The original concept of the Hawk, in its advanced training role, was to provide an aircraft able to represent many of the operational characteristics of the front line combat aircraft, within a limiting cost constraint both in design, development and production, as well as in operating costs.

Thus the aircraft was conceived as a small subsonic aircraft, built around an existing production engine of reasonable fuel economy, at the start of its development life. The aircraft was sized on requirements for landing speeds appropriate for flying training and internal fuel for adequate endurance for the required training syllabus. This led to a modest take-off thrust/weight ratio ([illegible] .5) moderate wing loading and capability for good payload/radius.

From this design concept other characteristics were achieved appropriate to the advanced training role:

* Good field performance from low speed high lift capability and low wing loading
* Good climb capability from thrust/weight and lift/drag ratios
* Good operational radius of action with substantial payload
* Agility over subsonic Mach number range from low wing loading and combat thrust to weight ratio
* Capable of demonstrating supersonic operation in diving flight
* Good flying qualities through simple flight control system
* Good weapon/store carriage capability with minimal change in flying qualities.

These features, required for the training role, include many of the necessary characteristics of a combat capable aircraft and through the aerodynamic, performance and weapon system developments envisaged lead to a highly capable attack aircraft.

In essence the development philosophy is based on the good payload/radius capability which can be developed for combat applications:

* Substantial weapon loads from hot or high operational bases delivered to distant targets
* Combat air patrol with air strike capability at substantial distance out from base or longer patrol time closer in
* Performance and flying qualities appropriate to target acquisition in air-air weapon attack, delivery of ground attack weapons and anti-shipping strike.

In pursuance of this development to the required combat capability the essential developments are in aerodynamics, performance and weapon systems, within the basic Hawk airframe and the affordable engine and equipment availability.

AERODYNAMIC DEVELOPMENTS (FIG. 1)

The flying qualities and performance characteristics referred to in paragraph 4 have been the subject of design studies and wind tunnel development tests at low speed, high speed and at high Reynolds number leading to flight trials.

Improvements of wing performance from the T Mk.1 wing configuration have been achieved without major structural changes.

At low speeds, through flap systems and wing flow control improvements the usable high lift has been increased by 15%.

At higher speeds the usable maximum lift has been increased by 28% at M = 0.5 and by 22% at M = 0.8. Initially improvements in the control of flow separation gave higher usable lift through better handling to higher angle of attack. Further improvements were obtained from application of leading-edge camber, modification of rear airfoil section to improve rear loading and use of rear camber by partial flap deflection.

Additionally, aerodynamic developments for weapon and external fuel tank carriage have been necessary to increase attack effectiveness through range/payload capability. In general these improvements have been realised through wind tunnel and flight development tests. The Hawk configuration, with a moderate sweep and aspect ratio wing, and wing section designed for high subsonic Mach number, is tolerant of store additions under the wing with minimal changes in longitudinal stability and centre of gravity. Thus a wide range of store types and configurations has been possible in the development of combat configurations.

6. ENGINE DEVELOPMENTS (FIG. 2)

In parallel with evolution of the aircraft from the training role, progressively towards the Light Attack role, the need to improve performance, compatible with operational roles and weapon delivery, has required progressive engine development.

Primary interest has been in improvements in operations with heavy loads in high ambient temperature at airfields above sea level and in maintaining combat performance particularly in low level attack.

The engine is a development of the non-reheated Adour engine designed for the Jaguar aircraft. It was selected for Hawk because of its new technology (at the time), its moderate operating temperatures and pressures, and rugged construction.

The first mark of Hawk Adour was designated the Mk. 151, and was MoD funded for the Hawk T Mk. 1 aircraft.

An uprated version designated Mk. 861/861A was developed with PV funding for Mk. 60 series export Hawks. Thrust improvement at SL, ISA, static conditions is 10%. Changes include a modified LP compressor, revised turbine nozzle and exhaust mixer areas, modified fuel system and new HP and LP turbine blades.

The Mk. 871 engine is the latest standard of Hawk engine. The uprating is achieved by increasing the max LP speed by 4% to 108% and raising the turbine entry temperature limit. The major changes (over Mk. 861A) are shown on Fig. 2. The Mk. 871 engine still features state of the art technology, leaving scope for still further growth with the use of advanced compressor and turbine technology in the future.

These engine developments have been achieved without significant changes to the basic engine dimensions and optimisation for other climates is also possible.

Typical changes in engine characteristics in the development from T Mk.1 to 200 Series are:

* Static thrust increase I.S.A., S.L.	13%
* Thrust increase at 0.8 M, I.S.A., S.L.	41%
* Static thrust increase I.S.A. +35°C, S.L.	26%
* Thrust increase 0.8 M, I.S.A. +35°C, S.L.	38%
* SFC change at Maximum Rating, I.S.A., S.L.	-2%

7. SYSTEM DEVELOPMENTS

The systems fitted to the Hawk T Mk.1 were kept as simple as possible, but with sufficient capability to achieve the desired training task. Thus the basic navigation is achieved using a twin gyro platform and conventional radio and radio navigation equipment. In the advanced flying training role no weapons system is fitted, in the weapons training role a gyro gunsight is fitted, together with a simple stores management system to control the centreline gun, and the training stores carried at the inboard wing pylons. This capability is extended for the T Mk.1A to allow the use of operational weapons.

For the Mk.50 and 60 Series a more comprehensive weapon control system is fitted, allowing the carriage of up to nine weapons. A wide range of weapons has been cleared on the aircraft, including air-air missiles. In all cases the export Hawk aircraft are very comprehensively furnished with radio and radio navigation equipment to meet individual customer requirements.

An up-dated, programmable, version of the weapon management system will shortly be introduced, allowing even greater flexibility for future operational stores. The system is currently being installed in the BAe demonstrator G-HAWK and will fly this year.

BAe recognised that there would be a need for training on more advanced avionic systems, and that, for operational use, it would not be possible to rely on beacon based navigation aids. Thus an Enhanced Ground Attack (EGA) system has been designed and is now running on a ground proving rig which includes a full Hawk cockpit and visual displays. This facility enables the system to be flown and demonstrated, and will be used during the future expansion and development of the system.

The system employs an Inertial Navigation platform, a Head-Up Display, Head Down multi-colour display and Hands-on-Throttle and Stick (HOTAS) controls. Coupled with the new Weapon Control System, and a comprehensive standard of radio and conventional standby displays the cockpit of the EGA Hawk should satisfy even the most demanding of pilots!

The EGA system can be fitted to a two seat Hawk, designated the Mk. 100 Series, for both training and operational use. The use of a MIL-STD 1553 B Data Bus simplifies the addition of such equipment such as Forward Looking Infra-Red (FLIR) sensors, and Laser ranging.

The EGA system also forms the heart of the operational single seat Hawk, the Mk. 200 Series. This aircraft has been designed to allow the greatest possible degree of flexibility to meet individual customer requirements. The aircraft is fitted with an inboard gun installation that can accept up to two 25 mm Aden guns, although the 30 mm Aden could be fitted if required. The use of a "gun pack" approach enables the gun bay to be used for other purposes if needed, for instance it would be simple to fit a specialised reconnaissance pack in lieu of guns.

The lines of the aircraft have been chosen with the possible fit of a modern multi-mode radar in mind. The hinged nose can accept a radar dish of up to 24" diameter. The use of a separate hinged nose makes it a simple task to cater for other equipment, such as FLIR and Laser, should the aircraft be intended primarily for day/night ground attack use. With a radar fitted the aircraft would be more suitable for an anti-shipping or air defence role.

Also under development are the electronic counter measures so essential today. The aircraft can be fitted with a radar warning system, and with chaff and flare dispensers. Active jamming pods can be carried on the wing pylons.

The system has been designed with considerable spare capacity to allow for future growth and gives the Hawk a remarkably comprehensive capability now and in the future.

8. PERFORMANCE (FIGS. 3 - 6)

The performance improvements in terms of mission effectiveness come from the increased capability for take-off with larger payloads, particularly in the "hot and high" conditions. In addition the improvement through development in attack speeds and agility enhances the combat capability to give overall effectiveness in the light attack role.

The developments to improve maximum lift, lift/drag ratio and combat thrust have been taken to a standard to enhance combat capability through higher agility at maximum usable performance conditions.

The sustained turn is improved to a higher level and also extended over a wider speed range to give better minimum turn radius and higher turn rates at operational attack speeds.

The instantaneous turn rate is achieved at low negative specific excess power and low turn radius, inside 0.3 n.m., and thus gives minimal speed loss in turning manoeuvres, typically less than 20% speed loss in 180° turns.

Also the 1 g acceleration is maintained at 5-7 kts/sec. up to the attack speeds and hence small speed losses in manoeuvre are quickly recovered.

Mission performance has been greatly extended by providing capability for take off with substantial payload, comprising combinations of air-air and air-surface attack weapons and fuel. In this way operation at substantial radius of action or for long times on station for air surveillance or reconnaissance missions can be achieved from relatively short airfields.

Typical gains in performance are:

* Take off distance at 3600 Kg. payload reduced 49%.
* From 4000 ft. runway take-off mass increased 20%.
* From 2500 ft. runway take-off mass increased 25%.
* Maximum level speed increased from .81 to .85 M at S.L.
* Sustained turn 15 deg./sec. from 0.3 to 0.75 M and minimum turn radius .22 n.m. at S.L.
* Instantaneous turn 22°/sec., .28 n.m. radius at S.L.

Also typical mission performance achievable is:

* Airspace denial (Hi-Hi)	4 hours on station at 50 n.m. (Missiles,gun)
* Close Air Support (Lo-Lo)	130 n.m. (5000 lb. bombs, guns)
* Interdiction (Hi-Lo-Hi)	530 n.m. (5000 lb. bombs, guns)
* Reconnaissance (Lo-Lo)	380 n.m. (Pod, missiles)
* Anti Shipping (Hi-Hi)	Strike at 800 n.m. radius (Sea Eagle)
* Ferry	2000 n.m.

9. CONCLUDING REMARKS

Hawk evolution, through the concept of an advanced flying training aircraft with potential for light attack operational capability, has been carried through at an affordable level.

The objective in this design evolution has been to make available a series of aircraft with considerable commonality and resultant benefit to costs of ownership of a mix of aircraft in the series.

At the present time the development has been taken as far as:

Maximum operating weight increased 50%

Maximum disposable load increased 125%

Maximum range increased 65%.

The planned evolution has been indicated in this paper and extends into the next decade, developing systems and performance towards improving operational capability to meet role requirements for specific customer scenarios.

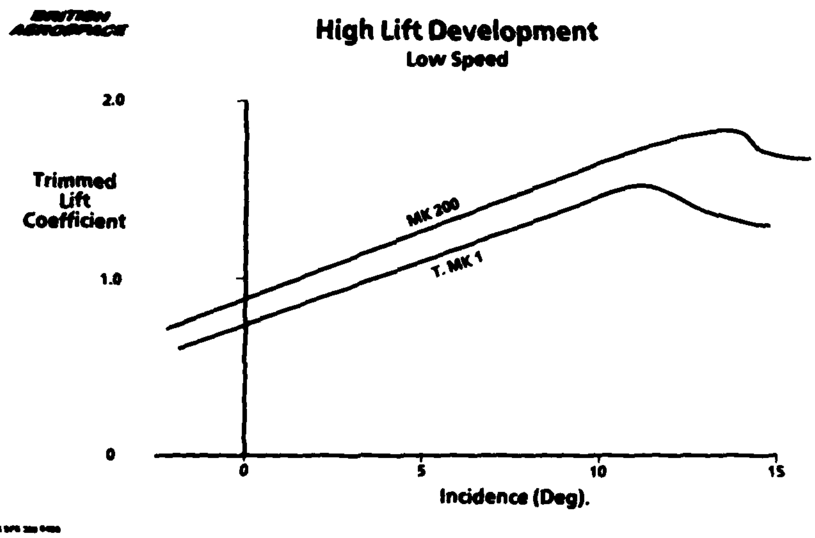


FIGURE 1A

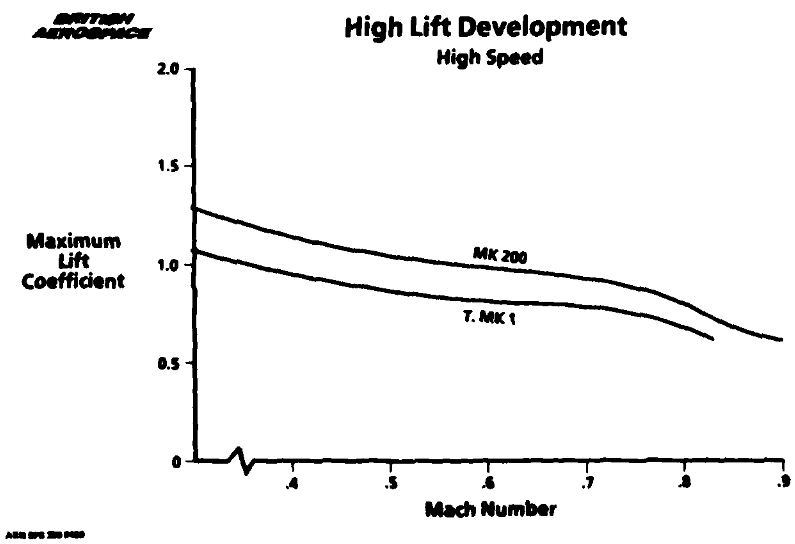
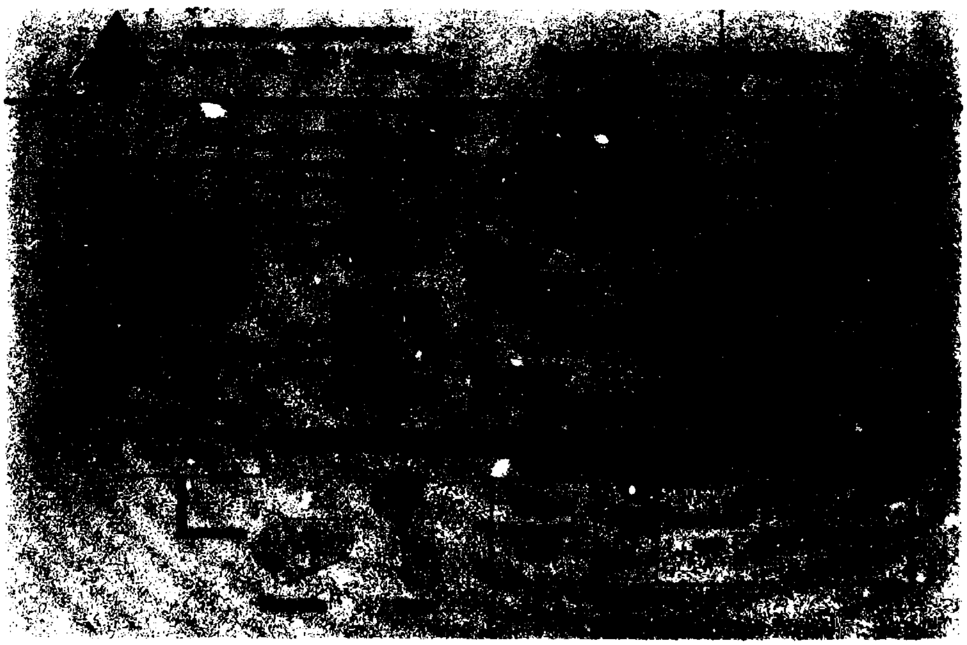


FIGURE 1B

FIGURE 2



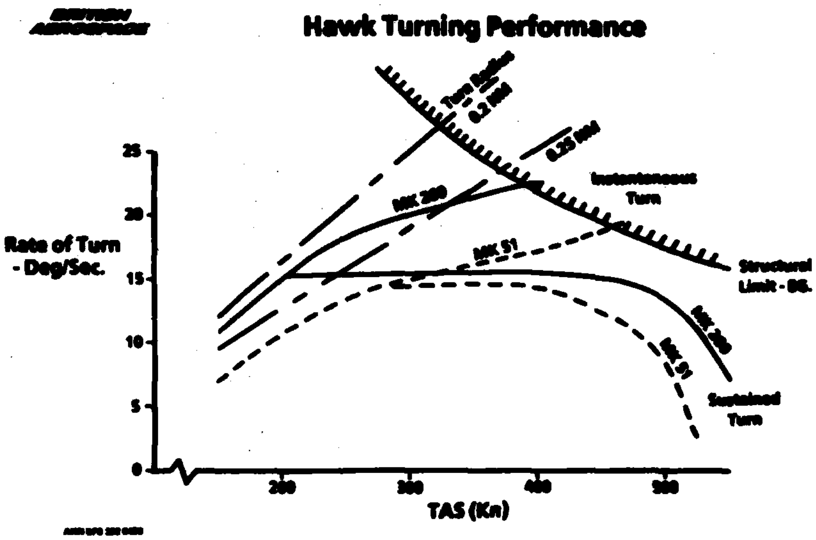

Hawk Turning Performance
Rate of Turn
- Deg/Sec.
25
20
15
10
5
0
200
300
400
500
TAS (Kn)
Turn Radius
0.2 NM
0.25 NM
Instantaneous
Turn
MK 200
MK 51
Structural
Limit - 8G.
MK 200
MK 51
Sustained
Turn

FIGURE 3

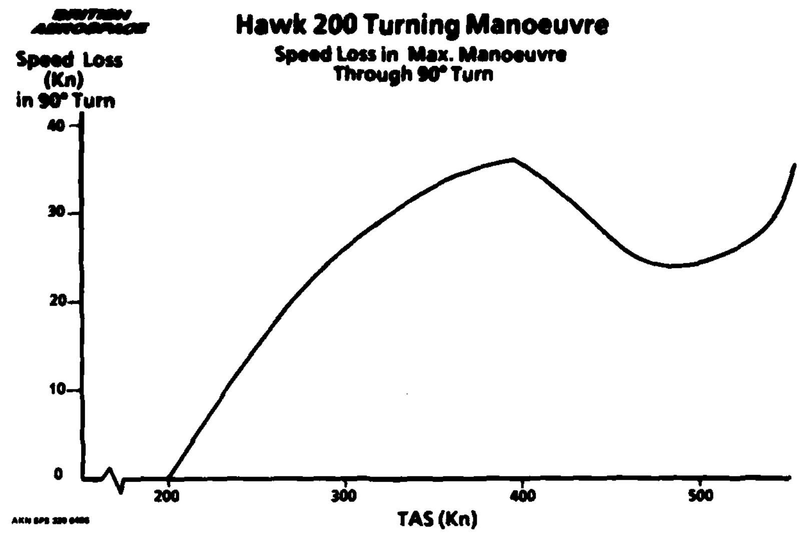


FIGURE 4A

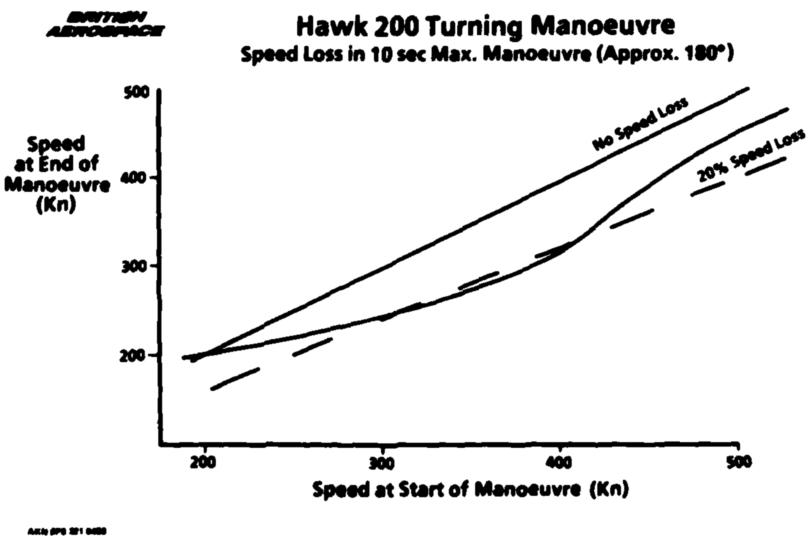


FIGURE 4B

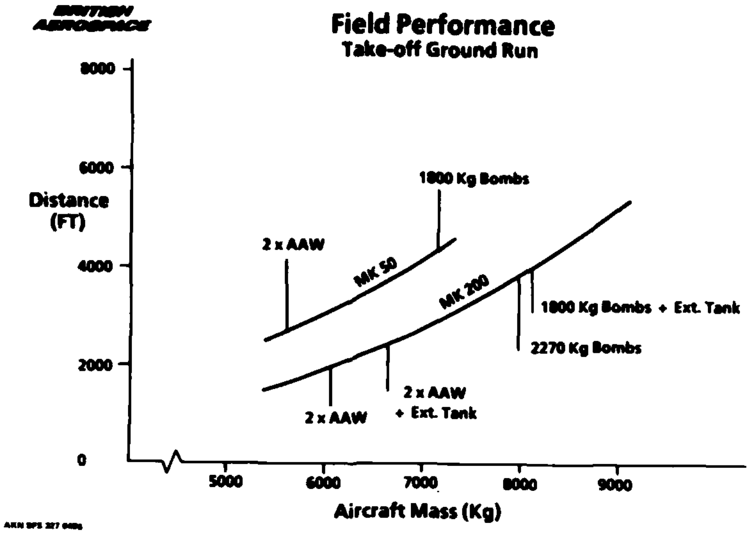


FIGURE 5

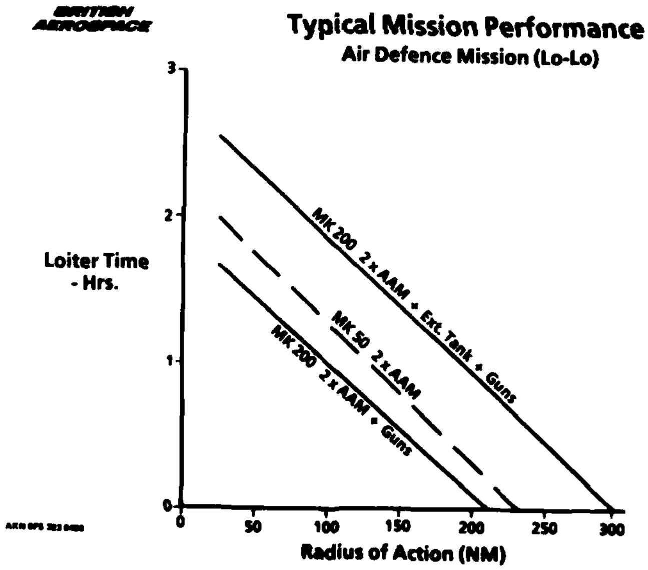


FIGURE 6A

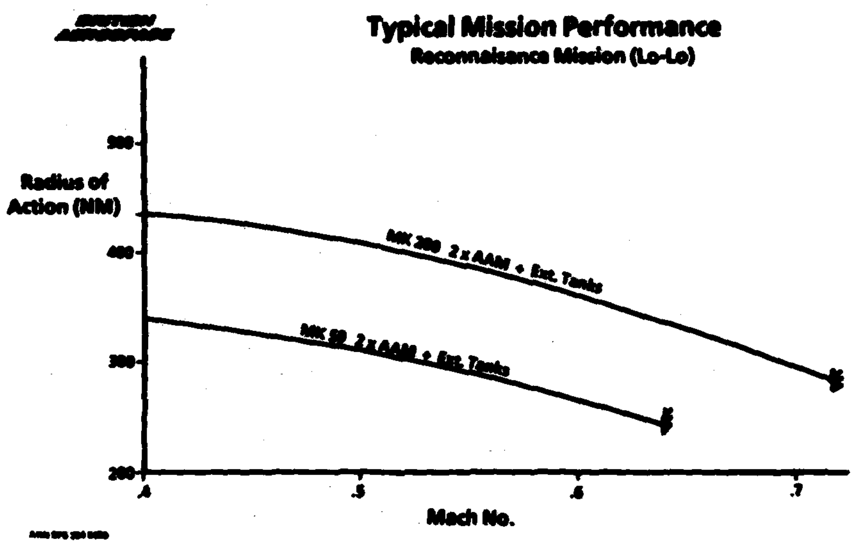

Typical Mission Performance
Reconnaisance Mission (Lo-Lo)
Radius of Action (NM)
MK 200 2 x AAM + Ext. Tanks
MK 60 2 x AAM + Ext. Tanks
400
300
200
.4
.5
.6
.7
Mach No.

FIGURE 6B

AD-P005 615

INTEGRATED DESIGN OF STRUCTURES

by

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ABSTRACT

It is shown that for highly sophisticated, naturally unstable airplanes flying supersonically a joint strategy to lay out the flight control system whilst minimizing design loads must be adopted. The selection of control surface geometry must be performed utilizing all possibilities from overall structural optimization including aeroelastic tailoring for primary carbon fibre structures.

In the proposed design philosophy the behaviour of the elastic airplane structure must be introduced and optimized in the very early design stage.

It is shown in the paper that the required control surface hinge moments can be reduced by optimizing mass penalties and efficiencies. Minimizing installed hydraulic power supply has also a beneficial effect on engine performance at low speed, high altitudes.

INTRODUCTION

An integrated structural design procedure was always applied to produce light-weight aircraft structures in the past. The method used largely depended on the experience and the creativeness of the chief designer. For modern naturally unstable airplanes with carbon fibre structures flying to supersonic speeds the application of

- detailed structural finite element models,
- early simulation results for flight control system performed with "elastified" derivatives,
- tuning of FCS to minimize loads whilst still respecting performance requirements,
- optimization methods to fulfill constraints such as strength and stiffness simultaneously with minimum weight

is mandatory in an even preliminary design stage. In this paper it is shown how aerodynamic loads are determined, how dependent they may be on FCS design and how aeroelastic tailoring is applied together with geometrical parametric studies to achieve maximum roll rates with minimum structural weight /1/, /2/, /4/.

Care Free Handling and Manoeuvre Load Control

A flight control system for a naturally unstable aircraft will limit design parameters - such as accelerations, acceleration rates, velocities, attitudes - in such a way that limit design loads are not exceeded. These design loads are defined in an iterative process between the FCS design, the loads group and the aeroelasticians. A few examples of how this is performed and how load envelopes are produced are shown below. A fighter aircraft is presented in Fig. 1. Its primary control surfaces are:

- inboard flaperons
- outboard flaperons
- foreplane
- rudder

Inboard-outboard flaperons and/or foreplane can therefore be used for trimming and controlling the longitudinal aircraft motion and it depends on the allocation of stick inputs to these control surfaces.

Fig. 2 shows an example of how much the foreplane and wing trailing edge flap loads can be affected by an appropriate choice of the initial trim contribution. This applies for the subsonic region - where the aircraft is unstable longitudinally - as well as for the supersonic region - where the aircraft is stable.

It is interesting to note, that the aircraft needs only small control deflection angles for initiation of the manoeuvre - as expected - but the control deflection immediately has to be checked to a large extent in order to stop the effect of the instability. Therefore no similarity of the stick input in comparison to the actual control surface deflections can be seen subsonically, whilst supersonically the usual increasing control deflection is seen in order to command a steady max. 'g' condition.

If the foreplane/flap schedule is only chosen from a handling and performance point of view, one may run into problems with the design loads on both surfaces, as one gains advantages on both surfaces by choosing an optimum loads concept. As demonstrated for trim we tried to show the effect of controlling the aircraft alternatively by foreplane or trailing edge flaps. Fig. 3 shows this effect for the pitch manoeuvre starting at the near optimal trim of F/P = -5°. Again it can be seen, that the contribution of either foreplanes or trailing edge flaps can strongly affect the respective control surface loads, at least for the supersonic case. It must be noted that for demonstration of these cases a given control system has been degraded by changing the assignment of foreplane/flap command and feedback paths which may be seen in the non-optimal motion of the 'g' time history (Fig. 3). Fig. 4 illustrates the problem, that MIL-Spec. requirements no longer represent generally usable structural design conditions for a carefree handling aircraft. It can be seen, that the MIL-triangular stick displacement initiates a full 'g' manoeuvre with associated high positive and negative pitch rates and operationally unacceptable acceleration rates - resulting in high inertia loads - for the pilot. The carefree handling aircraft on the right side of the diagram is controlled to its max. 'g' by a full back stick and it can be seen that both the max. g-rate as well as the pitch rate are extremely cut down to operationally meaningful levels by the control system. Naturally, an immedate triangular reversal is stopping the manoeuvre initiation and one would not reach max. 'g' as with a conventional aircraft, where the pilot has to be very careful in performing a MIL-type triangular manoeuvre without exceeding the 'g' limits.

Finally, it should be emphasized that in designing the control system it is very important to feed in design loads aspects at a very early stage, as can be explained by Fig. 5. It may be accepted from a handling/performance point of view, to overfulfill the time to bank requirement by an overswinging control deflection. This clearly increases the control hinge moments and one simply achieves load reductions - in this case about 36% - by adopting the max. acceptable time to bank.

All the examples shown clearly illustrate the aerodynamic loads produce by manoeuvres depend on carefully chosen control laws/trim programs of the flight control system.

Real time simulations with measured aerodynamic derivatives, aeroelastic efficiencies and optimized control laws must be performed and maximum response parameters selected from time histories (Fig. 6). From these the actual design loads are derived.

Aeroelastic efficiencies of control surfaces can show large reductions vs. airspeed and Mach number (Fig. 7) and they must be carefully chosen initially so that not too many iterative steps are necessary and also so that the structural weight which is needed to fulfill certain efficiency requirements is not prohibitive (Fig. 8).

Static Aeroelastic Consideration

As already stated,there is a strong influence of the aircraft elastic structure upon control surface effectiveness (Fig. 7) as well as aerodynamic loading (Fig. 9).

This paper describes an approach of how high sustained roll rates can be achieved at high dynamic pressures with aeroelastic tailoring of a carbon fibre wing, whilst minimizing hinge moment demand and therefore hydraulic power and flow requirements.

A certain roll rate was chosen as design aim at Ma 1.6, 20000 ft, which makes the aircraft agile and competitive. All calculations were performed with the TSO-computer program /3/ with an MBB-modified optimization algorithm. The program can minimize the structural weight by proper laying of CFC laminates in direction and thicknesses fulfilling in this case static strength and efficiency (stiffness) requirements simultaneously. Because a plate model is used for structural representation quick changes of geometry, like flap size, are possible which would be very time consuming on a finite element model. On the other hand there is a certain loss of accuracy so that results should be taken as tendencies rather than fixed values of structural weight.

Aim of the Study

The aim of the exercise was to optimize the CFC wing laminates (with respect to weight) in thickness and direction - always fulfilling the roll rate required - in such a way that the lowest trailing edge hinge moments could be found. Flap size - chord and length - were varied parametrically. An estimate of the exchange rate of trailing edge hinge moments with weight is given in Fig. 10. This figure shows that halving necessary hinge moments could save about 60 kg weight.

In order to have all possible flap travel available it is necessary to do all required trimming with the foreplane.

Search for Optimum Trailing Edge Size

Due to strong influences of elastic deformations on stationary aerodynamic forces at high dynamic pressures the classical aerodynamic approach with rigid derivatives must be replaced by a method which optimizes the structural weight fulfilling the roll requirement. It should be emphasized that all parametric investigations must be done by optimizing the structure for every point investigated - which could mean different laminate thickness and directions for each point. A study taking an optimized structure for one point and analyzing another point could be misleading.

The study was conducted in two steps:

1. Find the maximum possible chord flap.
2. Define a split line for two flaps.

Investigated Flap Geometry

The scope of the study is shown on Fig. 11. Different inboard flap chords were not investigated because the requirement was also to get the largest chord flaps aeroelastically possible necessary to assure controllability at high subsonic Mach numbers where longitudinal static instability is the highest and flap angle may be restrictive.

Results

Fig. 12 shows the hinge moment and required flap angle to fulfill the roll requirement for flap I. It shows a steep gradient for hinge moment reduction near the strength design which flattens considerably at 40 kNm. Flap deflection shows similar behaviour. It should be noted that the flap deflection for the rigid wing cannot physically be reached with the given t/c ratio and material properties. Rigid flap in this investigation means a flap which is continously driven. Two optimization runs were made with flexible flap driven at two spanwise positions (0.2 and 0.5 wing span) which showed that flap angle goes up whereas hinge moment goes down. These results should not be applied as a general rule as is shown in Fig. 13. This figure presents results for flap II (40% outboard chord). The behaviour of hinge moment and flap angle is similar but 40 kNm. can be reached with less structural weight. When the flexible flap was introduced the flap angle went up considerably whereas the hinge moment did not reduce. A boundary for increasing the flap chord outboard is the flutter speed with tip missile and the request for a reasonable torsional box to get a high enough missile attachment stiffness. As a matter of interest flutter speeds of the clean wing were calculated and are presented in Fig. 14. From this figure it can be deduced that for the clean wing there is no difference between wing with flap I or flap II. Flutter speed increases with structural weight because torsion frequency goes up. In Fig. 15 v-g plots and vibration modes for one case are presented. In Fig. 16 the added mass (above the mass for strength design) as a function of the hinge moment is plotted. The optimum hinge moment is about 45 kN for a full span flap. The bigger chord outboard flap II was chosen for further investigations, because it clearly shows a total mass reduction, against flap I when installing about 45 KNm.

Flap Split Definition

In order to define the flap split spanwise two exercises were preformed. The full span flap was cut outboard down to 80% and 60% span - always fulfilling the roll requirement with an optimized structure. As shown in Fig. 17 this is the wrong way to go. Hinge moment and flap deflection increase above reasonable values of

40 kNm and 15°

and cannot be reduced by added mass because gradients are too flat.

In Fig. 18 the full span flap is cut inboard to 80% and 54% span. The hinge moment goes down now but deflection becomes marginal (close to 15°) when a 54% outboard span flap is used alone to fulfill the roll requirement. It is also impossible to install 30 kNm at such a far outboard position as 54%. Fig. 19 shows clearly that the optimum lies around 35 kNm installed hinge moment, which is lower than for full span flap (Fig. 16). A possible way to go is shown in Fig. 20 where a flap split is taken at 40% outboard flap span (referred to total flap span) and different flap angles are used inboard and outboard. Table 1 shows that it is best to use maximum deflection from outboard flap respecting the limits

20 kNm and 15° angle

because ratio $\dfrac{\text{flexible hinge moment}}{\text{flexible wing roll moment}}$

is : ~ 1.5 x better than full flap
~ 2 x better than inboard flap

Proposed Flap Split

The following conditions must be fulfilled:

- biggest possible outboard span flap with maximum angle
- not exceed 20 kNm with outboard flap
- not exceed 15° flap angle

Two cases could be calculated (without changing the aerodynamic grid) shown in Fig. 21. A split of 50% i/b and 50% o/b flap was selected. With a linear interpolation of Fig. 21 results this would give an outboard hinge moment of 22 kNm

Additionally two benefits of this configuration should be mentioned:

- same actuator could be used for i/b and o/b flap
- about 5 kNm hinge moment is still available at the maximum roll condition when 40 kNm are installed as a total.

CFC Wing Laminate Thickness and Directions

For the selected case the laminates are shown as isothickness in Fi. 22 . An unbalanced laminate was chosen because it gives lowest structural weight. It is interesting to note that the +45° layer of Fig. 22, which is primarily responsible for increasing flap efficiency, is increasing its thickness outboard to produce higher stiffness.

REFERENCES

/1/ FÖRSCHING, H.W.
Grundlagen der Aeroelastik
Springer-Verlag; Berlin-Heidelberg-New York, 1974

/2/ SENSBURG O.; ZIMMERMANN, H.
Impact of Active Control on Structures Design
Fighter Aircraft Design
AGARD-CP-241, October 1977

/3/ SCHWEIGER, J.; SENSBURG, O.; BERNS, H.J.
Aeroelastic Problems of a Tailless CFC-Sailplane
Second International Symposium on Aeroelasticity and Structural Dynamics,
Aachen, April 1985

/4/ GÖDEL, H.; HÖRNLEIN, H.; KEPPELER, D.; SENSBURG, O.
Modern Trends in Aircraft Structural Design
60th Meeting of the Structures and Materials Panel of AGARD,
San Antonio/Texas, 21-26 April 1985

Acknowledgement

The authors would like to highlight the valuable contributions to this paper which stem from various discussions on the subject with Hr. Rüdiger Kunz - Head of the project development MBB-UL - who is among the few people appreciating that an integrated structural design is a necessity to produce an agile competitive fighter aircraft.

Flap	Rolling Moment rigid kNm 1° defl.	Rolling Moment flex. kNm 1° defl.	Rolling moment effect.	Hingemoment rigid kNm 1° defl.	Hingemoment flex. kNm 1° defl.	Hingemoment effect.	flex. H/M / flex. R/M	H/M essential defl. kNm	essential defl. for Roll/Req.
full span rigid	42.33	22.51	0.352	5.352	4.653	0.869	0.2067	42.06	9.04
I/B only rigid	22.34	13.7	0.613	3.887	3.455	0.900	0.2521	31.23	9.04
O/B only rigid	19.99	8.8	0.440	1.335	1.199	0.899	0.13625	10.84	9.04
full span flex.	42.33	18.45	0.436	5.352	3.836	0.717	0.20795	42.27	11.02
I/B only flex.	22.34	11.56	0.518	3.837	2.842	0.741	0.2458	31.32	11.02
O/B only flex.	19.99	7.12	0.356	1.335	0.931	0.69777	0.1307	10.26	11.02

TABLE 1 I/B AND O/B FLAP II (RIGID AND FLEXIBLE)

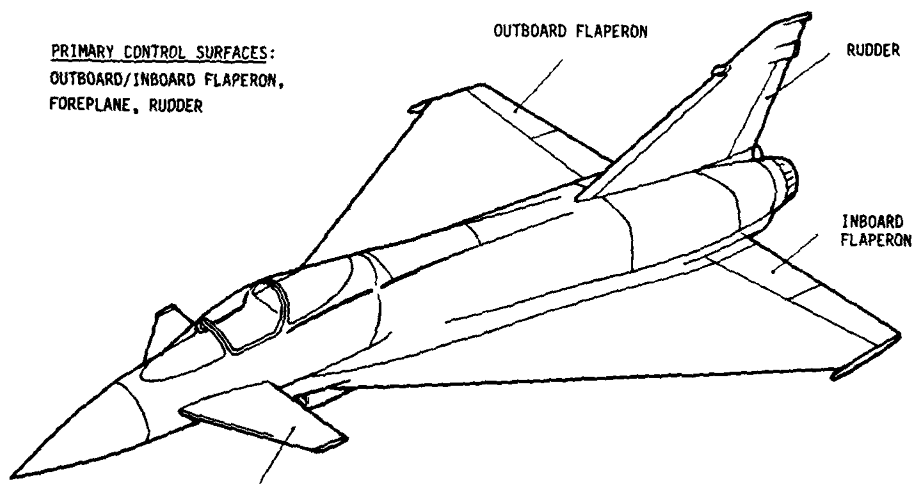


FIG. 1 AIRCRAFT CONTROL SURFACES

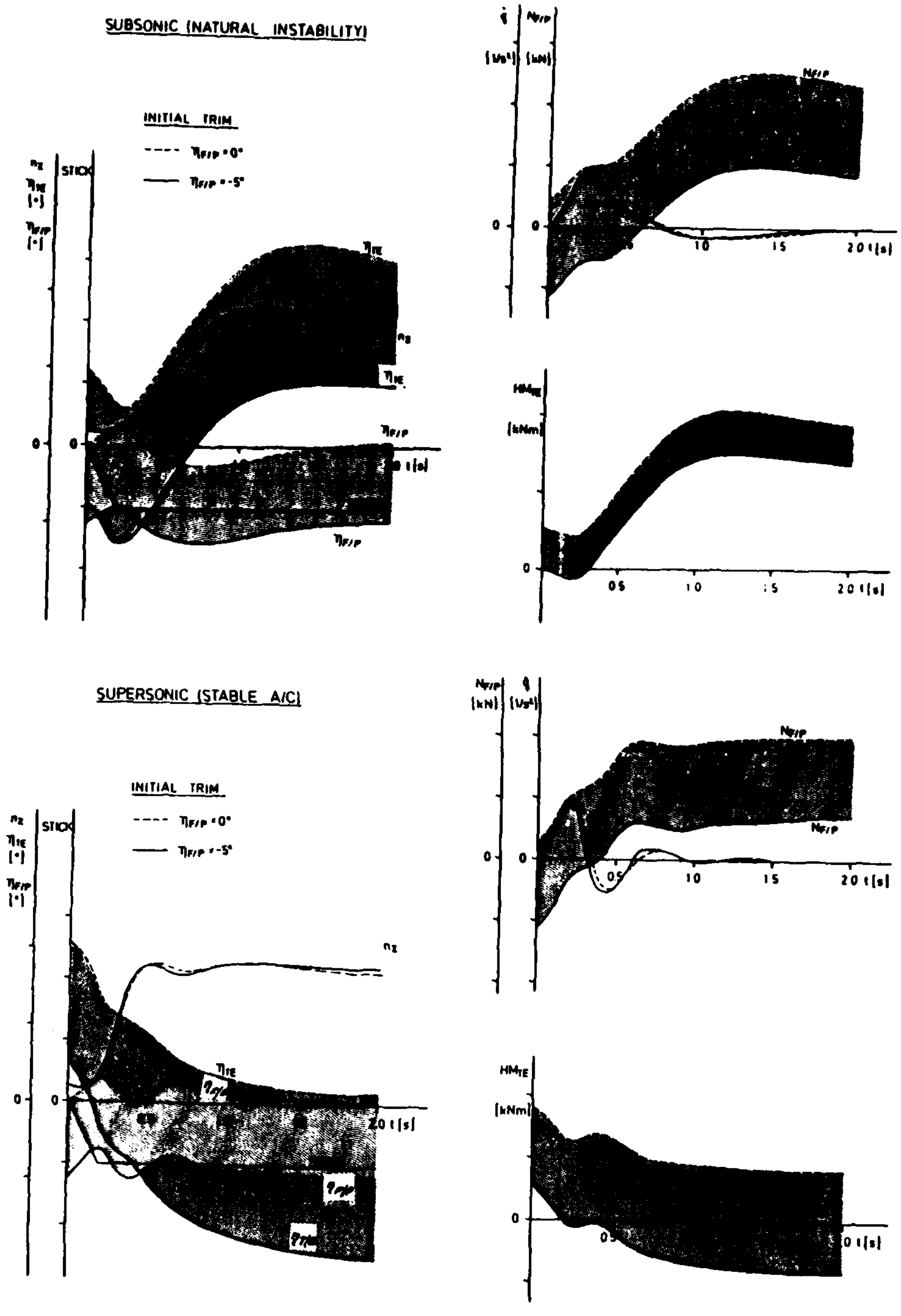


FIG. 2 ADAPTION OF TRIM CONTROL FOR LOAD OPTIMIZATION

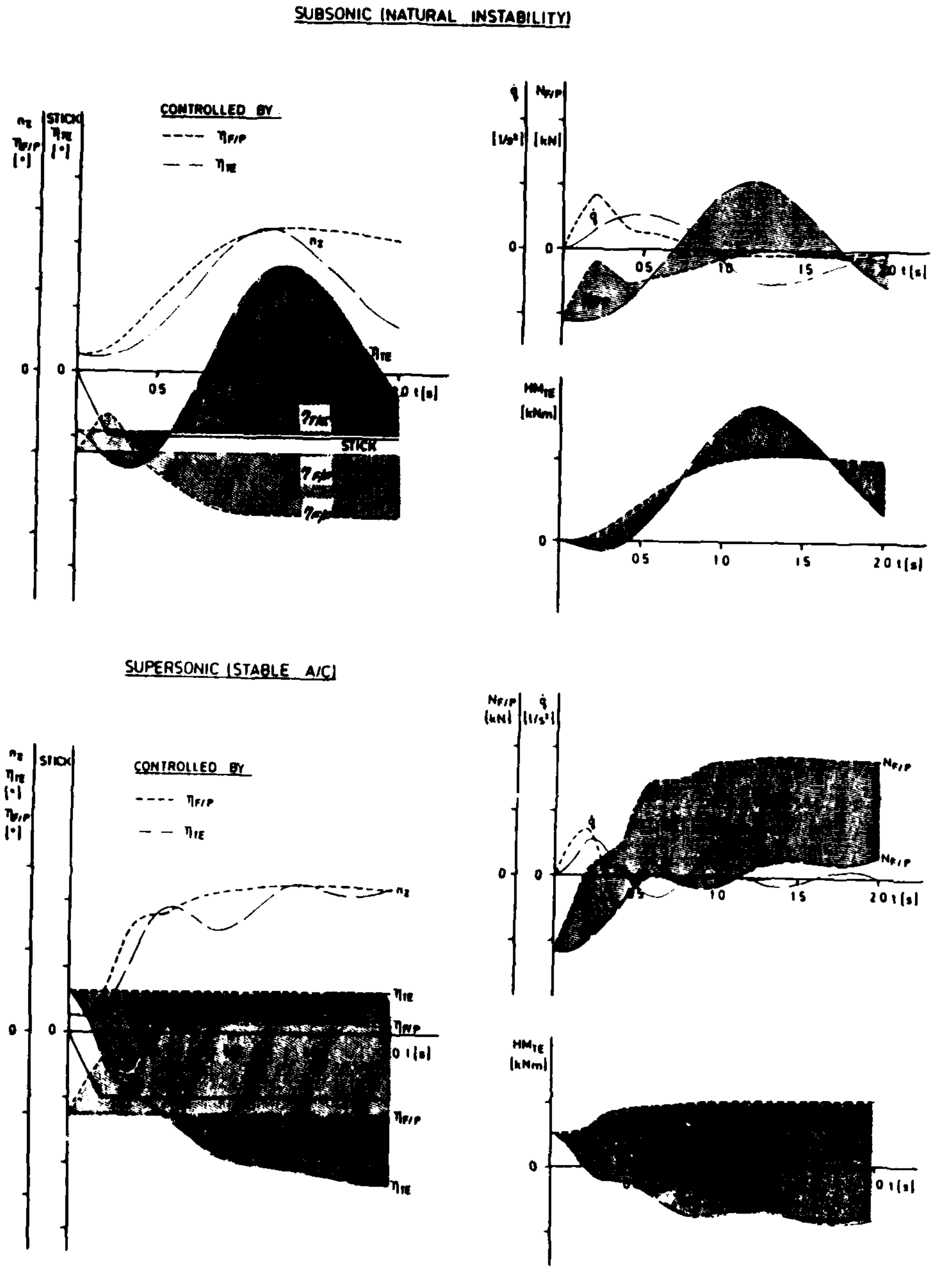


FIG. 3 ADAPTION OF DYNAMIC MANOEUVRE CONTROL FOR LOAD OPTIMIZATION

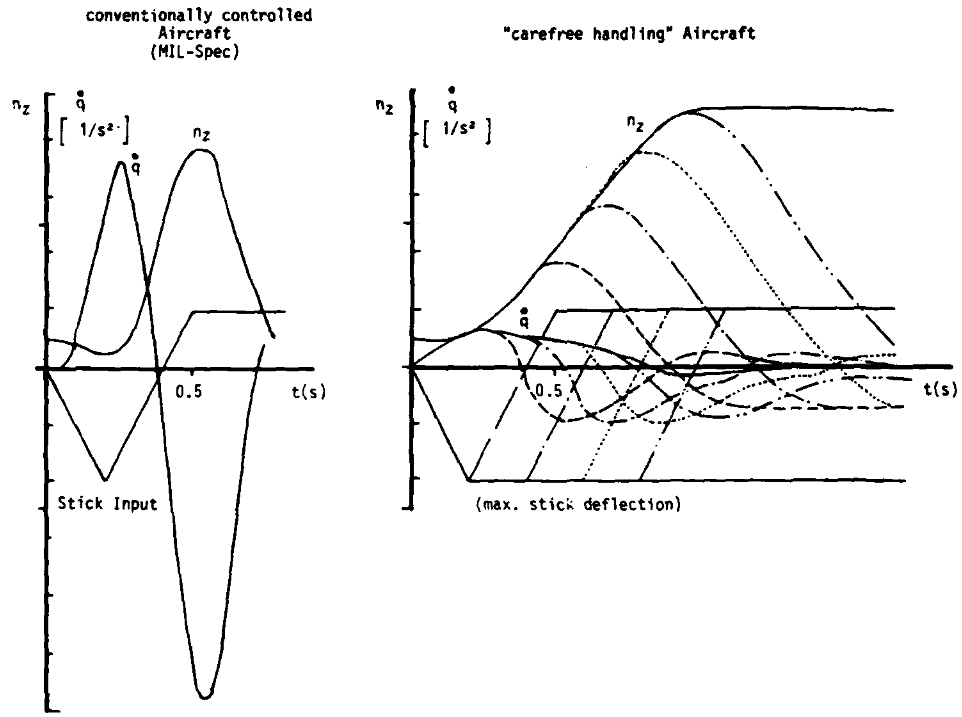


FIG. 4 COMPARISON OF MIL - SPEC & CAREFREE HANDLING MANOEUVRES

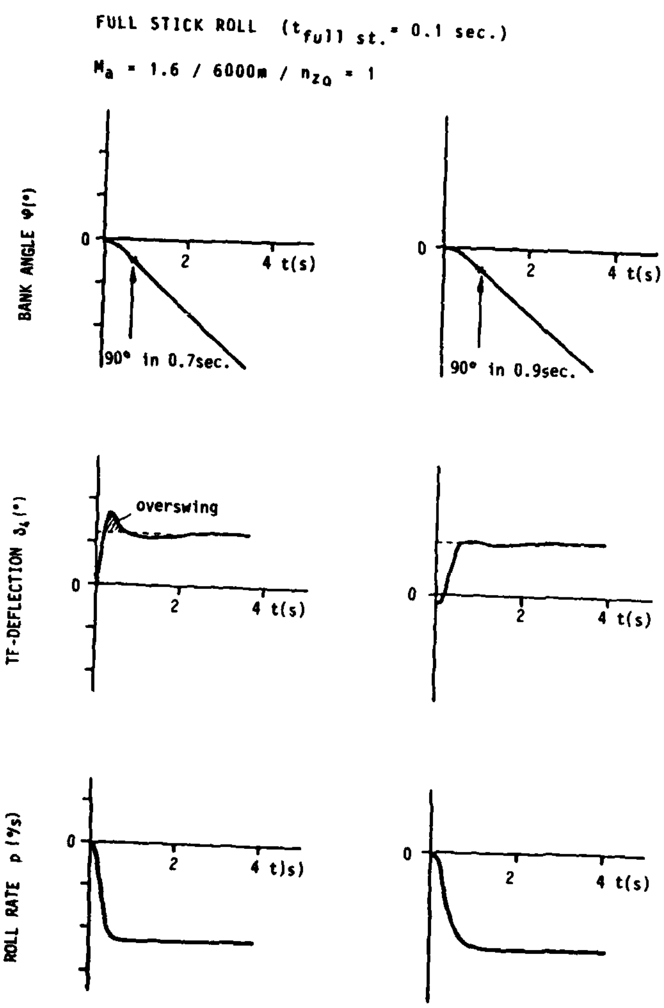


FIG. 5 ADAPTION OF CONTROL SYSTEM IN ORDER TO ACHIEVE 36% LOAD REDUCTION (TE - FLAP)

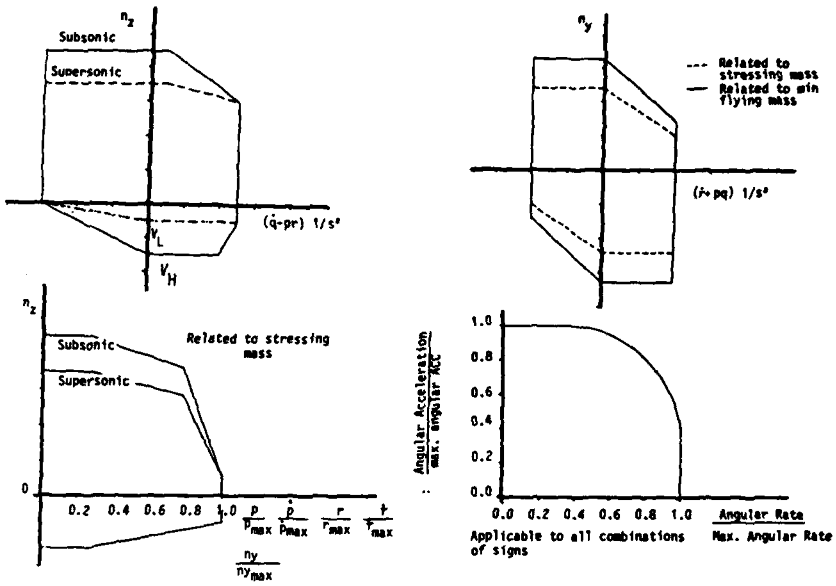


FIG. 6 FLIGHT PARAMETER ENVELOPES FOR STRUKTURAL DESIGN

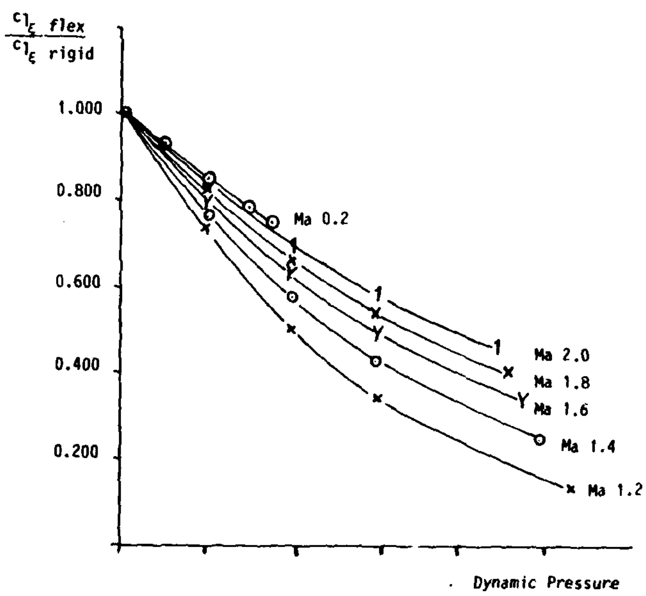


FIG. 7 AEROELASTIC CORRECTION FACTOR
TRAILING EDGE FLAP O/B

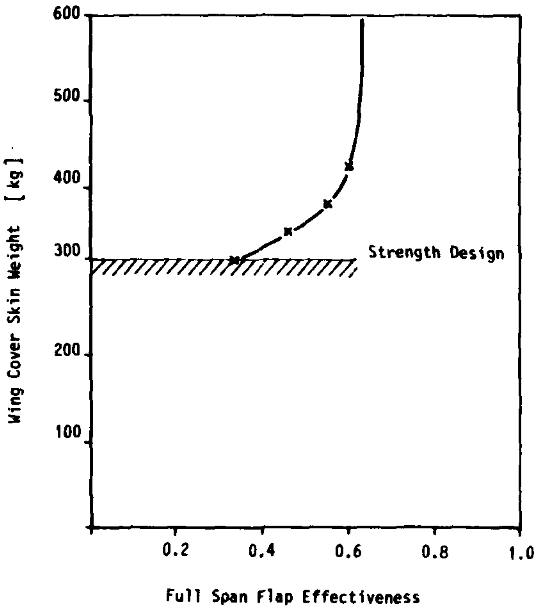


FIG. 8 REQUIRED STRUCTURAL WEIGHT FOR INCREASING ELASTIC FLAP EFFECTIVENESS REQUIREMENTS

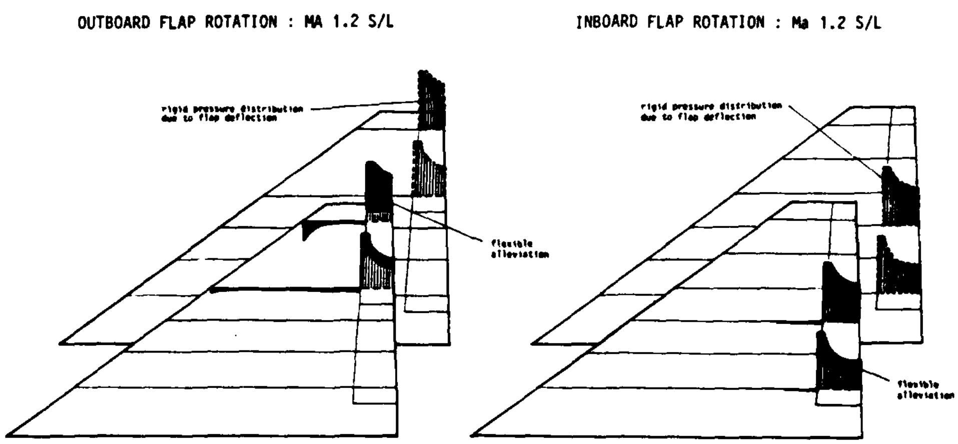


FIG. 9 ELASTIC PRESSURE DISTRIBUTION

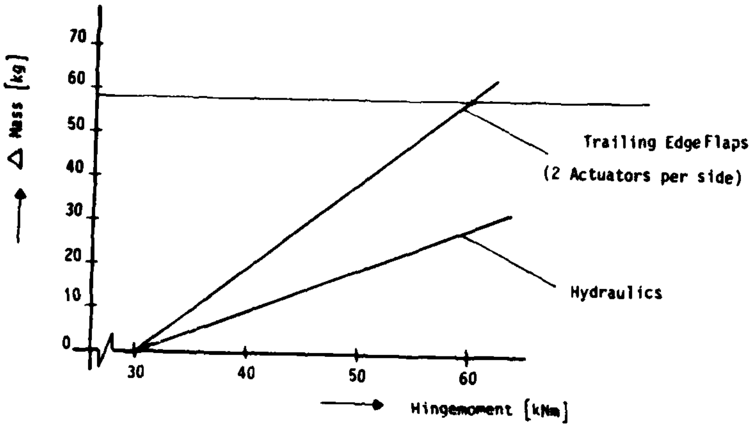
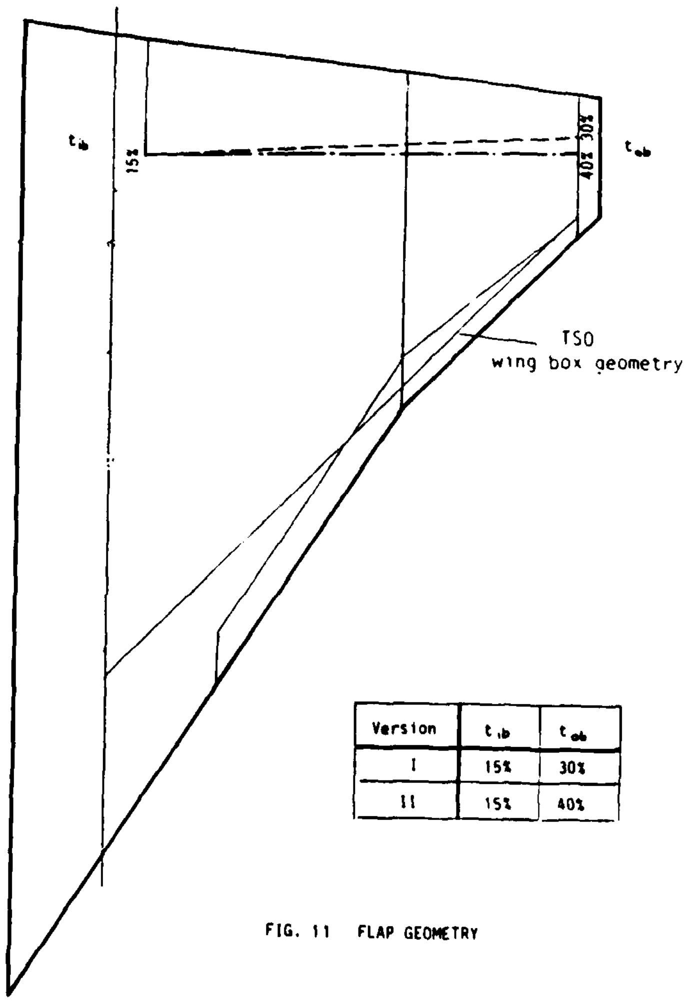


FIG. 10 ADDED MASS AS A FUNCTION OF TRAILING EDGE HINGE MOMENT



Version	t_{ib}	t_{ob}
I	15%	30%
II	15%	40%

FIG. 11 FLAP GEOMETRY

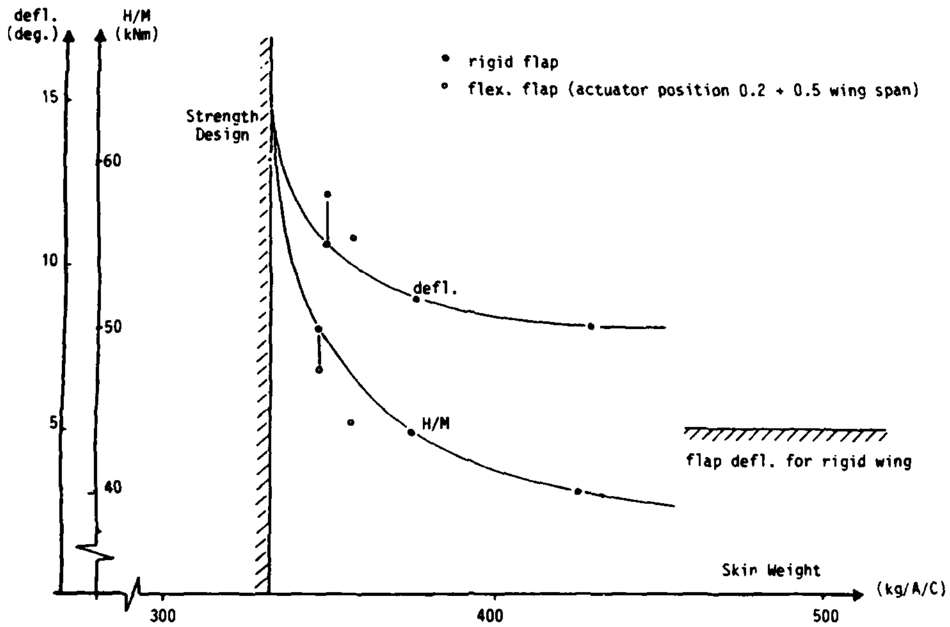


FIG. 12 DEFLECTION AND HINGEMOMENT FOR FLAP I
(Mach 1.6, 20000 ft)

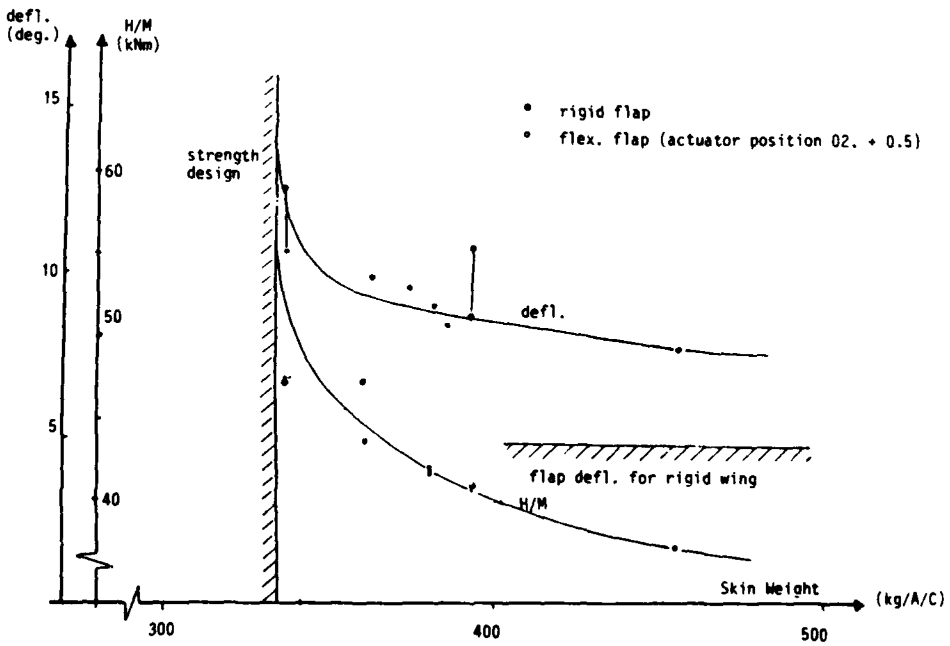


FIG. 13 DEFLECTION AND HINGEMOMENT FOR FLAP II
Mach 1.6, 20000 ft)

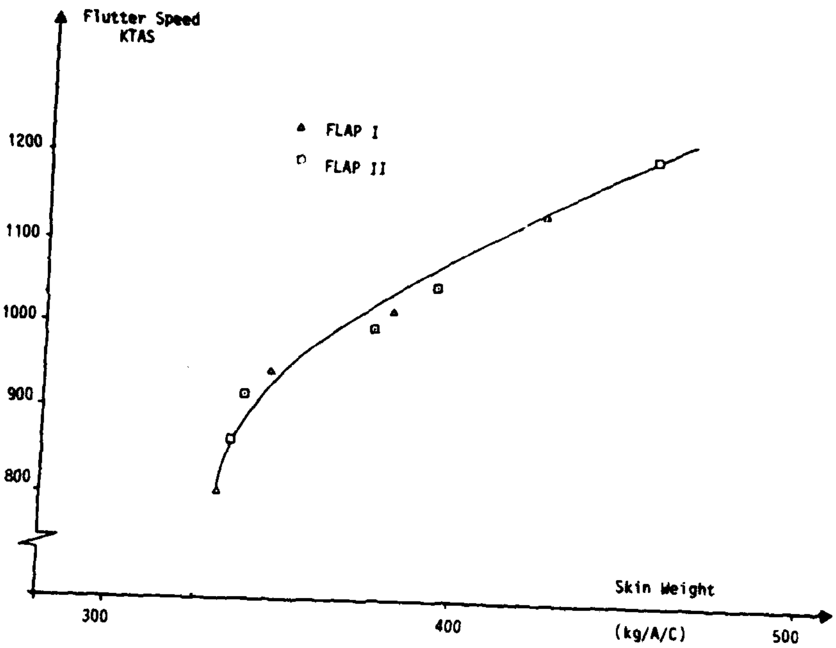


FIG. 14 FLUTTER SPEED VS SKIN WEIGHT

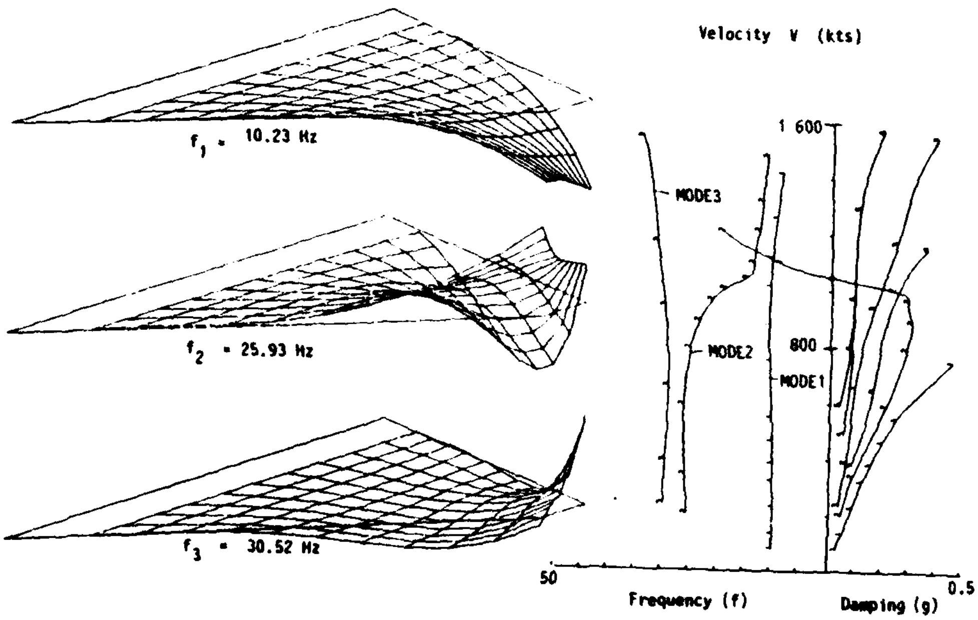


FIG. 15 V-g PLOT AND VIBRATION MODES FOR FLAP II

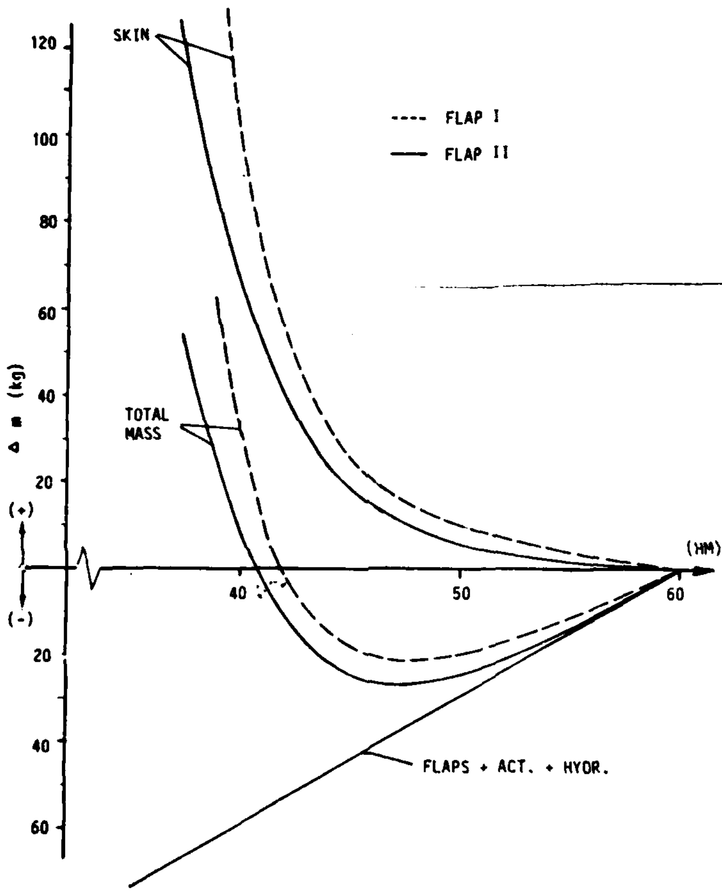


FIG. 16 ADDED MASS AS A FUNCTION OF HINGE MOMENT

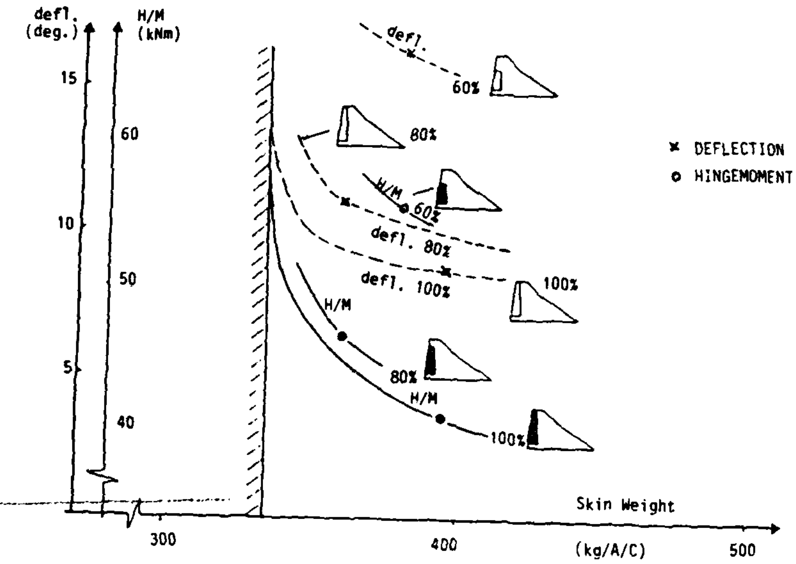


FIG. 17 VARIATION OF I/B FLAP SPAN (FLAP II)

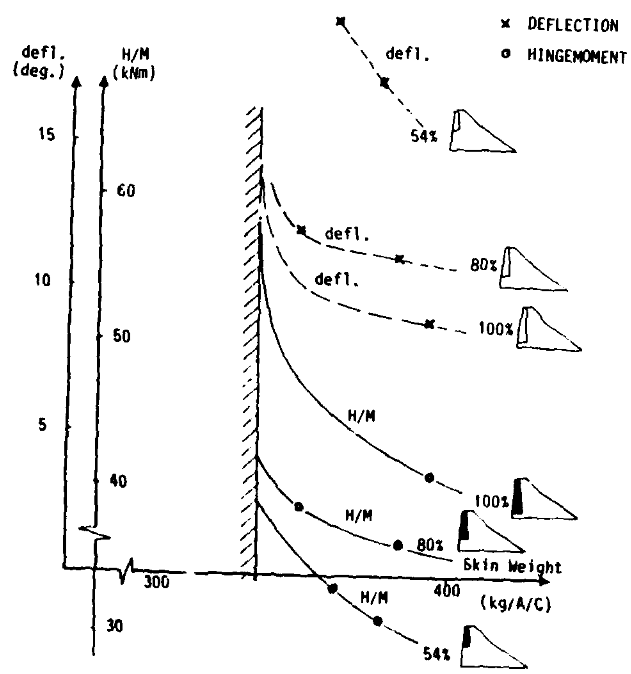


FIG. 18 VARIATION OF O/B FLAP SPAN (FLAP II)

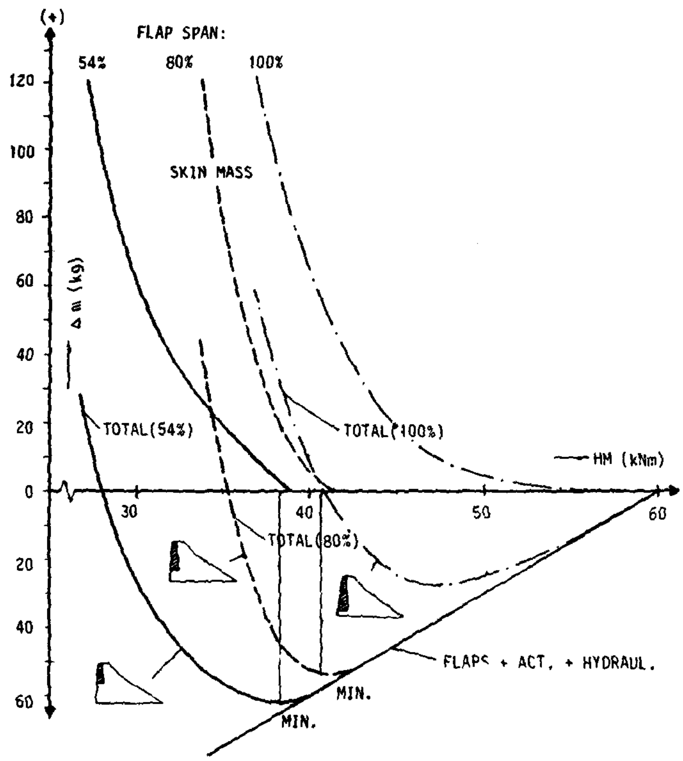


FIG. 19 ADDED MASS AS A FUNCTION OF HINGE MOMENT FOR VARIOUS OUTBOARD FLAP SPANS

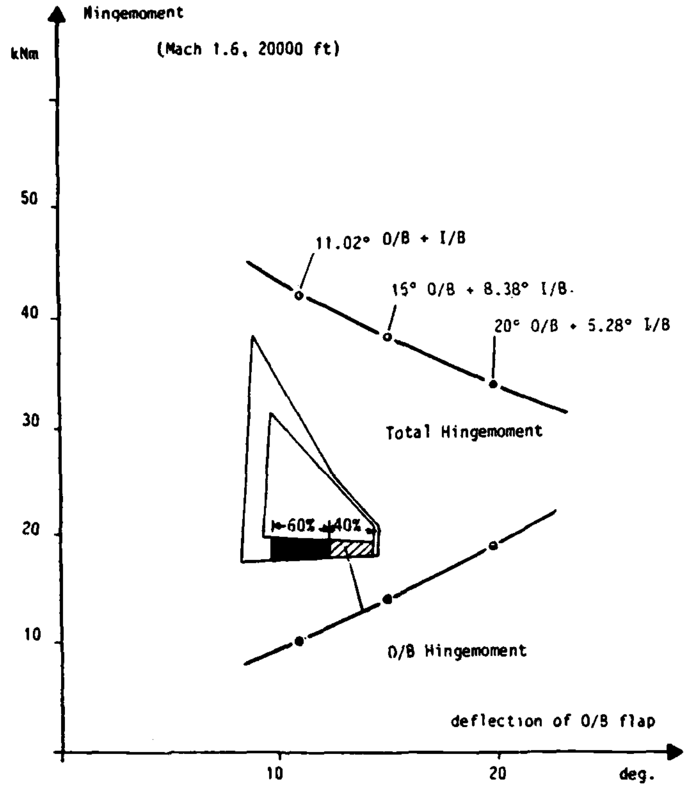
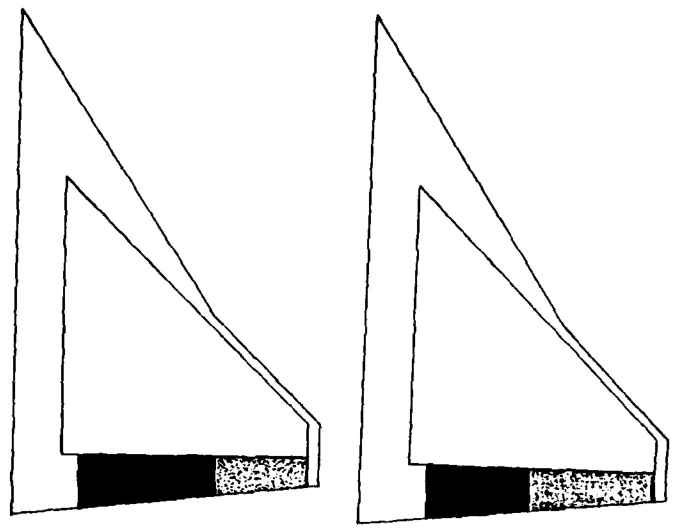


FIG. 20 COMBINATIONS OF I/B- AND O/B FLAP



Percentage Flaperon	60%	40%	46%	54%
Flap angle (IB/OB)	6.23°	15°	3.5°	15°
Hinge-Moment (IB/OB) (kNm)	23.8	14.0	8.38	24.98
Total Hinge Moment (kNm)	37.8		33.4	

FIG. 21 RESULTS FOR DIFFERENT FLAP SPLITS

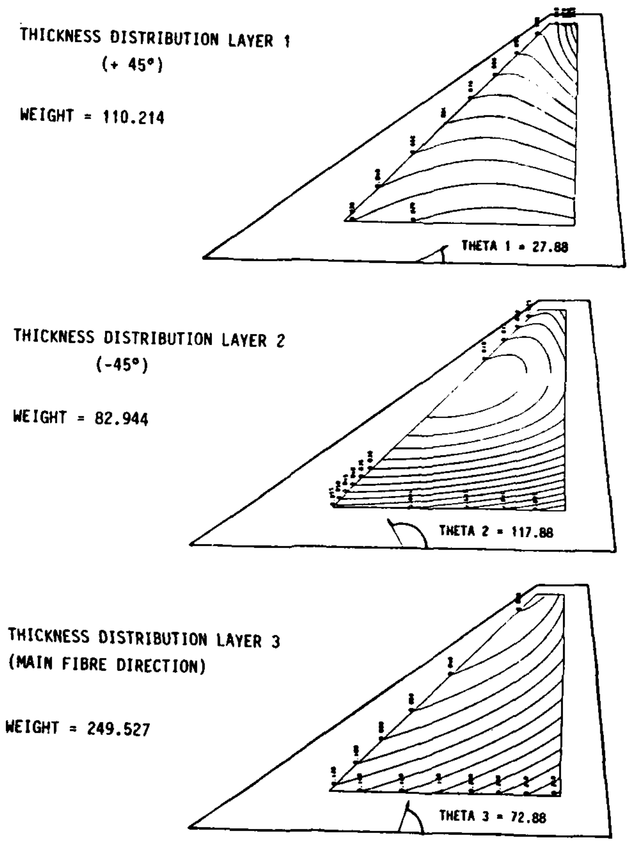


FIG. 22 THICKNESS DISTRIBUTIONS

AD-P005 616

PROPULSION SYSTEM TECHNOLOGIES FOR THRUST VECTORING

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APPLICATIONS FOR VECTORED THRUST

The Harrier/AV-8 aircraft, with its Rolls-Royce Pegasus engine, was developed primarily for vertical or short takeoff and landing operations. To achieve this it employs nozzles capable of vectoring through more than 90° to provide 'lift' and a reaction control system to provide aircraft control in low or zero forward speed operation. These features of the aircraft have also been employed to achieve a tactical advantage during combat by vectoring in forward flight (VIFFING).

Operational analysis studies have identified the potential combat advantage of post-stall manoeuvring (PSM) to improve rate of turn and vehicle/weapon pointing. To achieve any or all of these capabilities (ie V/STOL, VIFF and PSM) will require some degree of propulsion system thrust vectoring. Some particular requirements that the need for thrust vectoring place on the engine design and the technologies involved are addressed in this paper.

SHORT LANDING

A short landing capability is probably essential for the next generation of combat aircraft to ensure continued operation in the face of hostile airfield attacks. The achievement of a short landing run hinges on the attainment of a low stable approach speed as shown in Figure 1. A target landing run of 1000 feet demands an approach speed of around 80 kts. This implies a relatively high level of powered lift with an approach thrust/weight ratio of 0.6 or greater and a thrust vector angle in excess of 60° being indicated.

If the aircraft is to be stabilized on the approach path with high vector angles a thrust vector line close to the aircraft's c.g. is essential if the aircraft is to be trimmed aerodynamically.

VECTORING IN FORWARD FLIGHT

Vectoring of the Pegasus nozzles in the Harrier/AV-8 during forward flight, even with the stick neutral, causes an instantaneous nose-up pitch change which can be used to bring weapons to bear. This pitch change also gives a short term increase in instantaneous turn rate. The USMC have found that by vectoring the nozzles for as little as one second they can attain a firing position. No other aircraft, old and slow or modern and fast, can decelerate more rapidly than the Harrier which, with nozzles at the braking stop, can decelerate at up to 50 kt a second. Only a few seconds of VIFF are needed for the Harrier to reach a part of the envelope that is unattainable by other aircraft.

The Reaction Control System (RCS) provides the ability to orientate the aircraft to enable the missile to lock-on to the enemy while both aircraft are in the low speed part of the manoeuvre. This 'point and shoot' technique has been developed by the USMC and has proved highly successful.

Figure 2 shows four examples where VIFFING and reaction controls are able to give the Harrier an advantage. An additional and all-important factor is surprise. The enemy cannot tell when the Harrier is applying VIFF as the nozzles are not easily seen (unlike airbrakes which can indicate when a deceleration is being initiated). In combat, the pilots will be mentally computing each other's next manoeuvres; the enemy will find this unusually difficult as, with the advantage of VIFF, the Harrier's behaviour is not visually predictable. Deceleration coupled with limited fuselage pointing are thus the main combat attributes of current VIFF aircraft.

POST STALL MEANOEUVREABILITY

Post Stall Manoeuvreability (supermanoeuvreability) is generally defined as the ability to manoeuvre and control the aircraft at angles of attack beyond the maximum lift point (see Figure 3). Post Stall flight at high angles of attack has been experienced with the Ryan X13 and other Vertical Attitude Take-Off and Landing aircraft. The X13, powered by a Rolls-Royce Avon turbojet, was controlled by exhaust jet deflection and thrust variation, with roll control supplied by air jets at the wing tips.

The ability to control and manoeuvre a tactical aircraft in this post-stall regime will permit short-term 'instantaneous' manoeuvres at low speeds to achieve small radii of turn and thus provide the aircraft with a tactical advantage in air combat.

A typical combat development into the PSM regime is shown in Figure 4. As incidence is increased beyond the maximum lift point there is some reduction in the lift coefficient, and thus the total normal aerodynamic force on the aircraft, tending to reduce the turn rate. The increased drag force also causes the aircraft to decelerate. As the incidence increases, however, the engine gross thrust component normal to the flight path becomes significant in relation to wing lift and turn rate will thus increase. Structural limitations preclude the use of PSM beyond about Mach 0.5, and the main tactical advantage will occur at speeds below Mach 0.2. The essential difference between a VIFF manoeuvre, as demonstrated on the AV-8B, and a PS manoeuvre is the attitude of the aircraft and the magnitude of the forces involved.

The realization of useful VIFF/PSM performance hinges on the ability to generate adequate control forces when normal aerodynamic controls are ineffective. These forces will therefore have to be generated by the engine through thrust vectoring coupled to the primary flight control system. Lift, and hence drag forces, tend to be larger on an aircraft executing a PSM than one VIFFING, thus correspondingly greater control forces are therefore required for a PSM aircraft.

AIRCRAFT CONFIGURATIONS FOR THRUST VECTORING

The requirements of STOVL and PSM/VIFF are also quite different in terms of thrust centre control. While the STOVL requirement demands thrust vectoring with no significant pitching moment, VIFF/PSM demands pitch and yaw moments from the vectored gross thrust for rapid manoeuvring. The conventional aircraft configuration, as shown in Figure 5(a), with the thrust center located well aft of the c.g. of the aircraft, can utilize nozzle concepts with a limited vector angle capability to achieve PSM.

Projected STOVL configurations using an unmixed engine, such as shown in Figure 5(b), have the potential to combine both VIFF and PSM capability. If the rear nozzle of this STOVL aircraft is given the ability to move independently of the side nozzles in both pitch and yaw, it may provide the control power for PSM while retaining the pure VIFF and V/STOL capability.

PROPULSION SYSTEM TECHNOLOGIES FOR VECTORED THRUST

The requirements which will be imposed upon the propulsion system by the need for thrust vectoring and PSM operation are as follows.

- Capability to vector the primary thrust in pitch and yaw rapidly and reliably.
- Reaction control system for roll control (at least).
- Integrated flight and propulsion control system.
- Surge-free operation of the engine with the intakes at high angles of attack.

We will now look at each of those requirements in turn and address some of the solutions available.

NOZZLE CONCEPTS FOR THRUST VECTORING

Counter Rotating Duct System shown in Figure 6 was developed initially for vectoring in the pitch plane but lends itself readily to all axis vectoring. The wedge angle between the two bearing planes determines the maximum vector angle. Synchronized counter rotation of the two moving sections will vector the thrust in a plane while differential rotation of the ducts will produce a vector in the third dimension. This system is only proposed for axisymmetric nozzles.

For applications where a fixed area nozzle is required a two bearing system is acceptable. If, however, a multi-function nozzle is required, ie with area variation, thrust reverse, etc., then to simplify the transmission of control and actuation power to the nozzle, it is desirable to prevent the nozzle from rotating by using a third bearing. By increasing the wedge angle between the bearing planes any vector angle can be achieved up to 90°. It is therefore mechanically feasible to develop a nozzle which provides both the two-axis vector capability for PSM, and the high vector angle required for VTOL and STOVL.

Spherical Bearing Concept again relies on bending the jet pipe upstream of the nozzle. The spherical bearing permits a modest degree of thrust vector in any direction, but does present some problems in mechanical design, both structurally and to minimize leakage. To alleviate the problems of load transfer across the spherical bearing a gimbal assembly can be used. This can be applied with either a spherical seal or the counter rotating duct concept to contain the airflow to the nozzle while removing the axial loads from the bearings. Only limited vector angles are achievable with either of these two concepts.

Swash Plate Concept. The potential for a lighter, more compact system can be achieved by integrating the vectoring function into the nozzle design. A unison ring employed to coordinate the movement of the convergent flaps can also act as a swash plate to asymmetrically control the convergent flaps angle and thereby produce a small amount of thrust vector. Such a system can be employed with both convergent and con-di axisymmetric nozzles. In the latter case the divergent flaps may be asymmetrically controlled.

Post Exit Deflector. Model tests have shown that a post exit deflector can produce deflection angles of 15-20° with only a small performance penalty. Such a concept can be integrated into a target type thrust reverser design as shown in Figure 7. In this example a two-door system is shown where independent deployment of the doors will deflect the nozzle flow. Penetration of the deflector door into the jetstream will determine the deflection angle, and the door assembly is mounted on a bearing concentric with the nozzle axis such that the desired thrust vector can be achieved by rotation.

Simultaneous deployment of the two doors will produce progressive levels of reverse thrust until the doors meet at the nozzle center-line and act as a conventional target thrust reverse system. The use of a 3 or 4 door system may eliminate the need for rotation by decoupled control of the doors.

Non-Axisymmetric Nozzle Concept. No range of multifunction nozzle concepts today would be complete without a non-axisymmetric option, therefore the design of a variable throat area, variable area ratio 2D con-di nozzle can easily be configured to provide limited thrust vector in the pitch plane. Various studies to incorporate a lateral force capability have looked at ports in the side walls upstream of the throat, hinged sidewalls down stream of the throat and vanes (powered rudder) in the exit flow.

While hinged side walls proved the most effective approach, simple ports in the sidewall are probably easier to engineer. Such a concept is shown in Figure 8. Ejecting approximately 10% of the flow normal to the mainstream flow axis will produce an effective yaw vector of 5°. However vectoring the total thrust is a more efficient way of producing the same yaw force since the Cosine loss of 5° thrust vector is much less than the axial thrust loss from 10% less flow through the main nozzle.

Each of the thrust vectoring concepts presented above has the potential to generate the necessary control forces for VIFF/PSM. Each concept however has its strengths and weaknesses which need to be addressed in development of a flight worthy system. Figure 9 summarizes some of the features of each concept and identifies limitations and specific problem areas of each.

REACTION CONTROL SYSTEMS

In hover and partially jetborne flight below the normal aerodynamic stalling speed, the conventional control and stabilizer surfaces have insufficient effectiveness and must be augmented by some form of reaction control system. For example, in the Harrier/AV-8, the RCS system makes use of engine HP compressor bleed air which is ducted to shutter valves located at the extremities of the aircraft fuselage and wings.

Figure 10 presents a comparison of 3 methods of providing pitching force on a typical tactical aircraft, namely:

(a) aerodynamically generated by elevators

(b) jet reaction by engine HP compressor bleed air

(c) jet reaction by vectoring the engine thrust.

It can be seen that at speeds below about 200 kts. a modest degree of engine thrust vector will provide more pitching moment than either the elevators or 10 lb/sec of HP bleed. Similarly for yaw, vectored thrust can provide the necessary power to stabilize and control the aircraft.

For roll control, some form of remote jet reaction is necessary and HP compressor bleed air is the logical choice. The use of LP compressor bleed for RCS has been studied in the past but the larger ducting required to pass the greater flow required to provide adequate forces, adversely affect the vehicle sizing and wing design. Figure 11 shows the rolling moment which can be generated by 5 and 10 lb/sec of HP compressor bleed flow relative to that generated aerodynamically by deflected ailerons.

The use of HP compressor bleed air for reaction control can affect engine operation and impact on the engine design. Specific features which have to be considered are:

o the need to increase turbine temperature to maintain total thrust (including the bleed thrust) especially in the hover mode with V/STOL aircraft.

- o changes to the combustion pattern factor, as a result of the reduced combustor flow and the bleed off-take location, affecting turbine component lives.
- o changes in the HP compressor working line as bleed is demanded.
- o changes in the engine control characteristics and the need to maintain engine protection and handling at various bleed flow levels.
- o changes to the engine internal air system and the effects on bearing loads and leakage.

To minimize the amount of bleed flow required and thus minimize the penalties and constraints on engine operation, ways of amplifying the effective thrust may be considered. Various systems have been studied and they fall into three basic categories:

(a) Energy increase by heat addition to the bleed flow by remote burners.

(b) Increased propulsive efficiency by energy transfer to increase mass flow at lower pressures. Such systems are rotary inductors, ejectors, fan/cold turbine.

(c) A combination of both a) and b) such as fan/hot turbine and hot bootstrap units.

An alternative approach is to use an auxiliary power source to provide the required reaction control force. These may be

(a) by direct air bleed from an APU

(b) by power off-take from an APU to drive remote air compressors/fan

(c) direct thrust from small rocket motors at the aircraft extremities.

INTAKE DESIGN

The demands on the intake are driven more by certain mission legs than by the fact that the vehicle has vectoring nozzles. An obvious requirement for V/STOL or STOVL is the flow capacity of the intake with little or no forward velocity. For a fixed geometry intake, auxiliary area such as blow in doors may be required. If high speed flight is a missions requirement then a variable geometry intake may provide the necessary area variations.

A further consideration for operation with vectored nozzles is the location of the exhaust jet efflux in relation to the intake, especially in ground proximity. Placement of the intakes can therefore affect the risk of hot gas reingestion and must be evaluated in the context of the specific vehicle and nozzle configuration.

The use of vectored thrust for VIFF does not place any specific requirements on the intake design since the intake incidence is within the range of normal operation. However for PSM the vehicle and hence the intake will be operating at very high angles relative to the line of flight. This presents some unique requirements for the intake designer who must ensure that adequate flow is delivered to the engine with acceptable levels of flow distortion and with no adverse effects on the engine handling or stability.

Operation of air intakes at very high incidence angles requires use of variable geometry features if operation at other points in the flight envelope is not to be penalized by design compromise. Figure 12 shows that satisfactory engine face distortion levels have been achieved at up to 70° incidence angle by use of a shielded intake with a variable cowl lip. Compare this with the rapid rise in distortion with incidence angle for a typical unshielded fixed lip intake.

The high incidence performance of shielded side mounted and chin intakes with variable cowl lip is also shown in Figure 12 to be acceptable over a wide range of Mach numbers. In general it is considered that the technology to develop an intake for operation at high incidence required for PSM exists and that these features can be integrated into a variable geometry intake to also provide good performance over the rest of the flight envelope.

FLIGHT/PROPULSION CONTROL SYSTEM INTEGRATION

In the vectored thrust mode the propulsion system will be an integral part of the aircraft flight control system as shown in Figure 13. This will create a number of interface considerations and design requirements unique to this application. The propulsion control system must provide adequate response, precision and stability to satisfy the aircraft handling qualities criteria. It must be reliable and incorporate acceptable flight safety features; it must be integrated with the inflight diagnostics system to maximize cost effectiveness; and it must be a lightweight, highly maintainable system that maximizes the operational suitability of the aircraft.

In addition to the conventional requirements for an advanced propulsion control system, when used with a vectored thrust engine the system must be capable of satisfying the following objectives:

Precise control of requested thrust levels including compensating for the effects of variable compressor bleed offtake.

Complete self-limiting engine protection with added complication of changes in engine running lines due to variable bleed and nozzle vector angle effects on nozzle area.

Mission reliability at maturity equivalent to that of the flight control components.

Control integrity which can be verified before starting and while running to indicate and display malfunction of any control module.

Propulsion system status and flight-critical data available for display via integrated inflight diagnostic system.

CONCLUSION

The four main propulsion system technology areas that need to be addressed for thrust vectoring are Vectoring Nozzles, Integrated Flight/Propulsion Control, Reaction Control Systems and Intakes. The order is also indicative of the level of effort necessary to develop each technology to an acceptable level. Figure 14 identifies some specific technologies within each area which need to be addressed. Some of these are specific to the thrust vectoring application and others, such as materials, are generic to any advanced aircraft application.

Numerous V/STOL aircraft projects incorporating vectored thrust have flown over the years and provide a unique background for the development of thrust vectoring propulsion technologies. Many of these technologies defined in this paper have been and are being addressed as part of the Rolls-Royce ongoing commitment to V/STOL.

Specific conclusions concerning the development of vectored thrust propulsion related technologies are:

Some degree of primary thrust vectoring will be required to provide the necessary control forces in pitch and yaw on future supermanoeuvreable tactical aircraft.

On such aircraft a reaction control system (RCS) will probably be required for roll control.

The design of intakes for high incidence, low Mach number operation should not present serious technical difficulty.

From the propulsion system viewpoint, all axis vectoring nozzles and their actuation systems present the greatest technical challenge.

Several advanced short takeoff and vertical landing (ASTOVL) aircraft concepts already incorporate vectored thrust based on demonstrated RR technology.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the assistance of their colleagues in the preparation of this paper.

The authors also thank the Directors of Rolls-Royce plc for their permission to publish this paper, although the views expressed are those of the authors and not necessarily those of Rolls-Royce plc.

The authors acknowledge that some of the nozzle layouts discussed may resemble those designed by other manufacturers but emphasize that the key to the achievement of acceptable performance lies in the detail mechanical design of the nozzle.

This work has been carried out with the support of the Procurement Executive, Ministry of Defence.

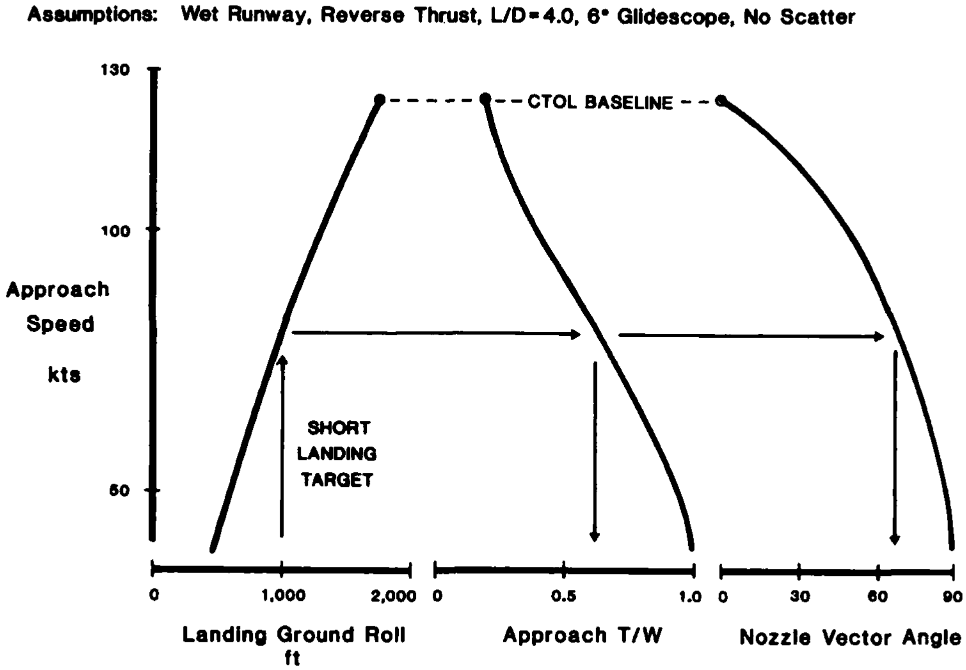


Figure 1 Short landing

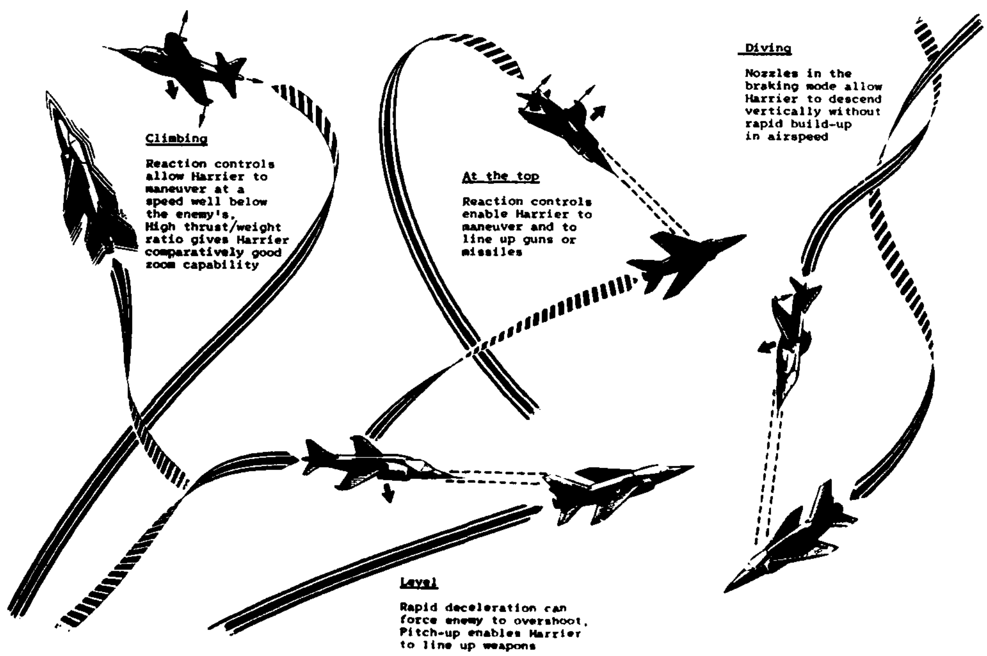
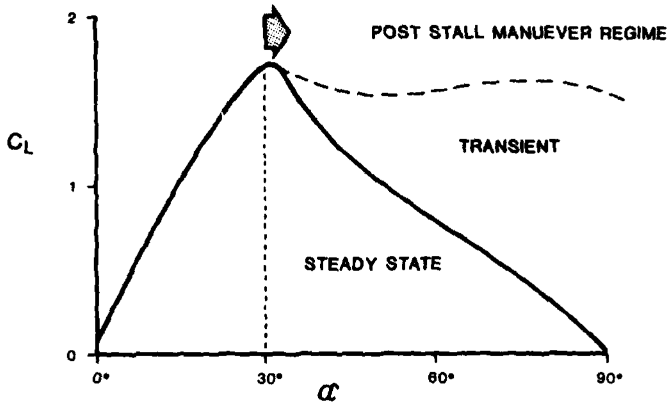


Figure 2 Advantages of vectoring in forward flight

- SUPERMANEUVERABILITY -

- **The ability to maneuver control the aircraft at incidence beyond maximum lift.**



- **Tactical advantage derives from short term instantaneous maneuvers and small radii of turn.**

- **Post stall flight has been experienced (E.G. Ryan X13) - Supermaneuverability demands more control power.**

Figure 3 Post stall maneuvering

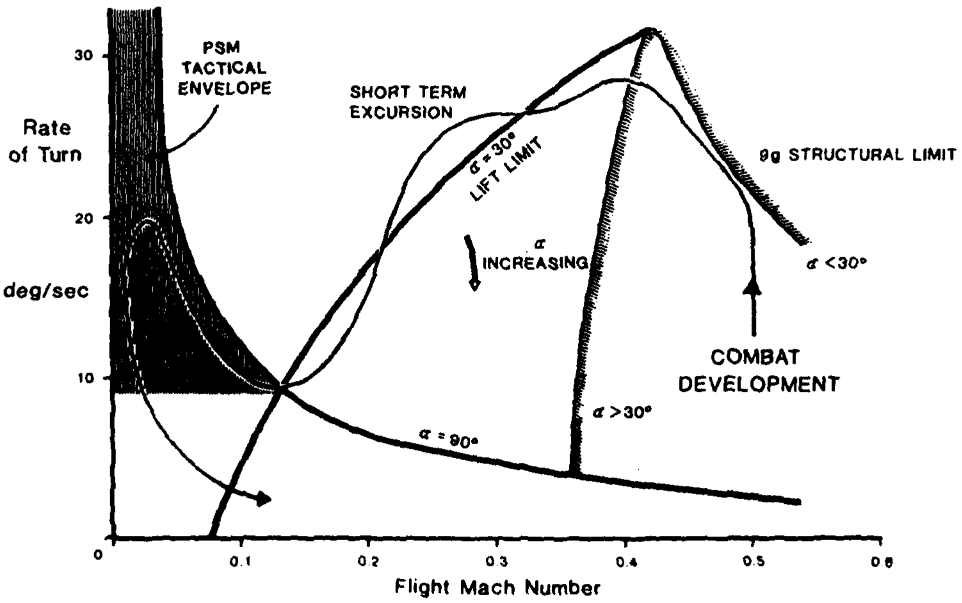
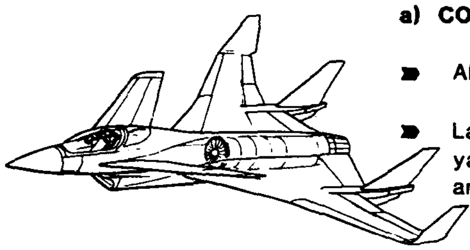


Figure 4 Operating conditions



a) CONVENTIONAL CONFIGURATION

- All axis vectoring of rear nozzle
- Large moment arm produces large pitch and yaw moments with modest thrust vector angles

b) STOL AIRCRAFT CONFIGURATIONS

- Independent vectoring of side and rear nozzles with all axis vectoring on rear
- Shorter moment arm requires larger thrust vector angle for same pitch moment but provides ability to balance aircraft on propulsive lift for V/STOL operation

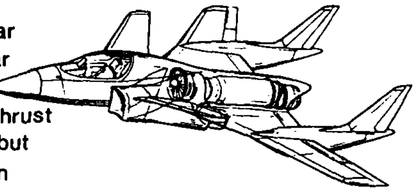
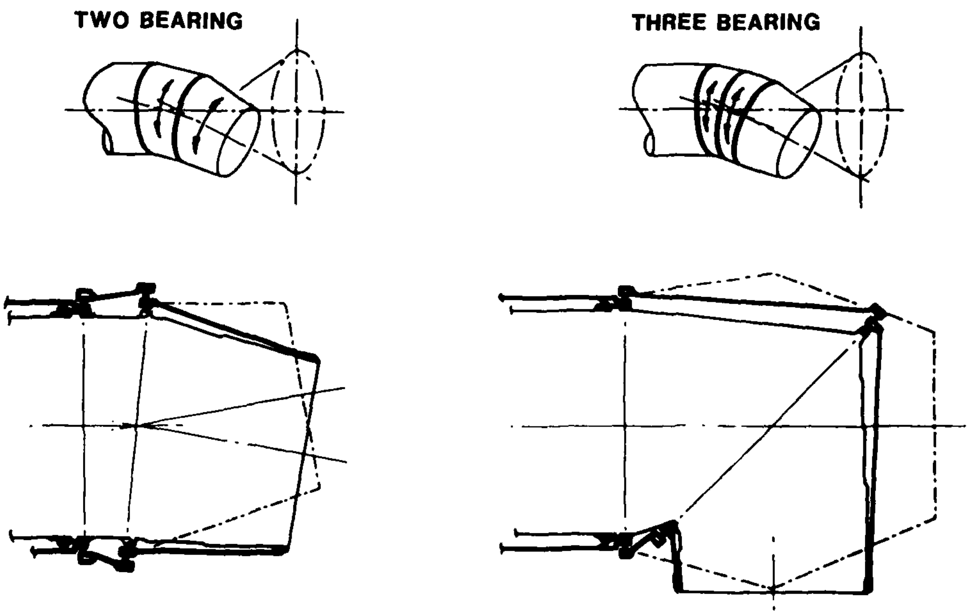


Figure 5 Aircraft configurations for thrust vectoring



Small (20°) Vector Angle

Large (90°) Vector Angle

Figure 6 Counter rotating duct concept

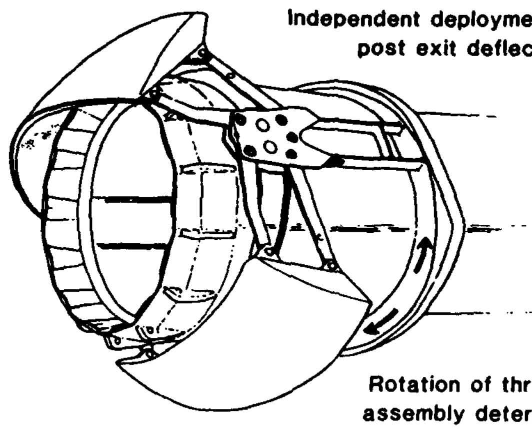


Figure 7 Rotating post exit deflector/thrust reverser concept

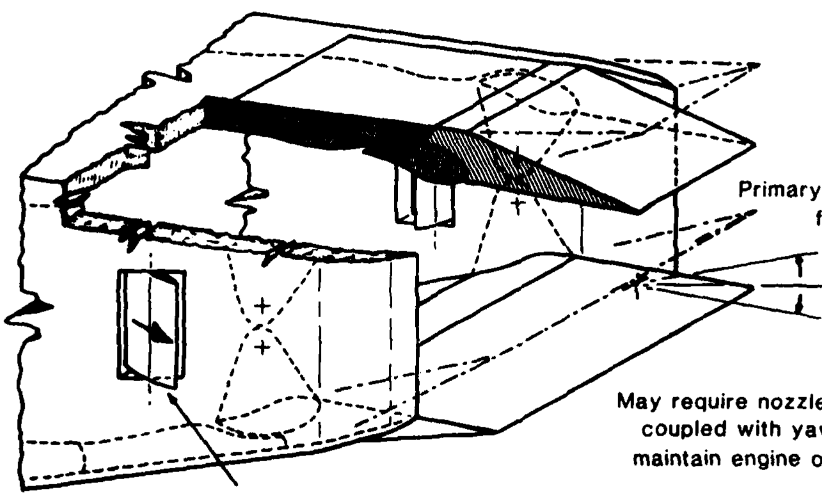
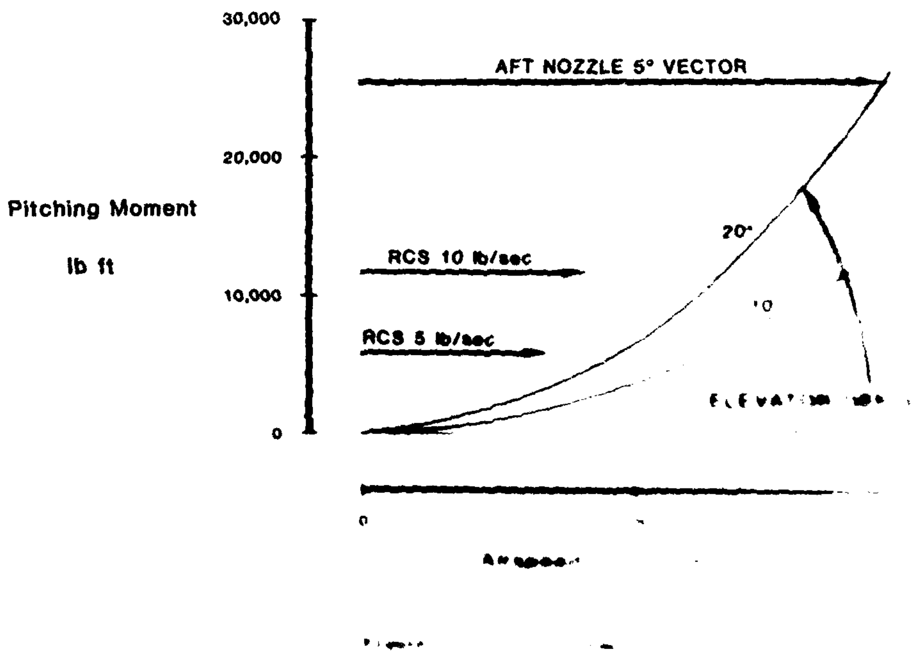


Figure 8 Vectoring 2D-CD nozzle with yaw port

Concept	Vector Angle Pitch	Vector Angle Yaw	Actuation Loads	Weight	Response Rate	Ease of Integration	Complexity - Mechanical	Complexity - Control	Sealing/Leakage	Comments
2 & 3 BEARING SYSTEM	○	○	○	◒	●	◒	○	◒	◒	Unlimited vector capability for V/STOL
SPHERICAL JOINT	◒	◒	●	◒	○	◒	◒	○	◒	Limited vector capability
GIMBALED JOINT	◒	◒	○	●	○	◒	◒	○	◒	Limited vector capability
VECTORING PETALS	◒	◒	●	◒	◒	○	●	○	●	High actuator loads. Lots of moving parts and leakage paths
SWIVELLING POST EXIT DEFLECTOR	◒	◒	◒	○	●	◒	○	◒	○	Simple but slow response. Integrates easily with thrust reverse capability
2D-CD with SIDE PORTS	◒	●	○	●	○	◒	○	◒	●	Limited yaw forces. High leakage

○ Good ◒ Moderate ● Poor

Figure 9 Summary of nozzle concepts



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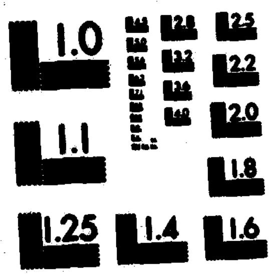

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

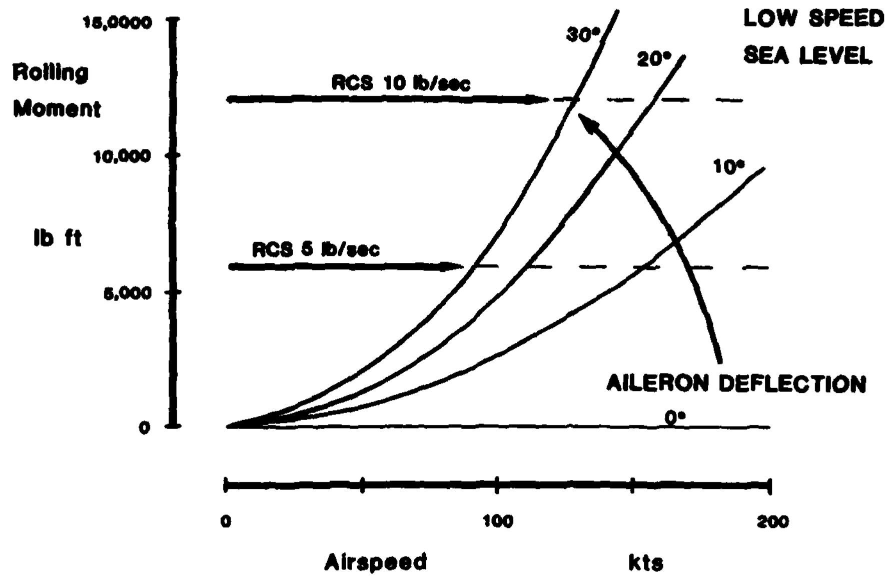

Figure 11 Roll power

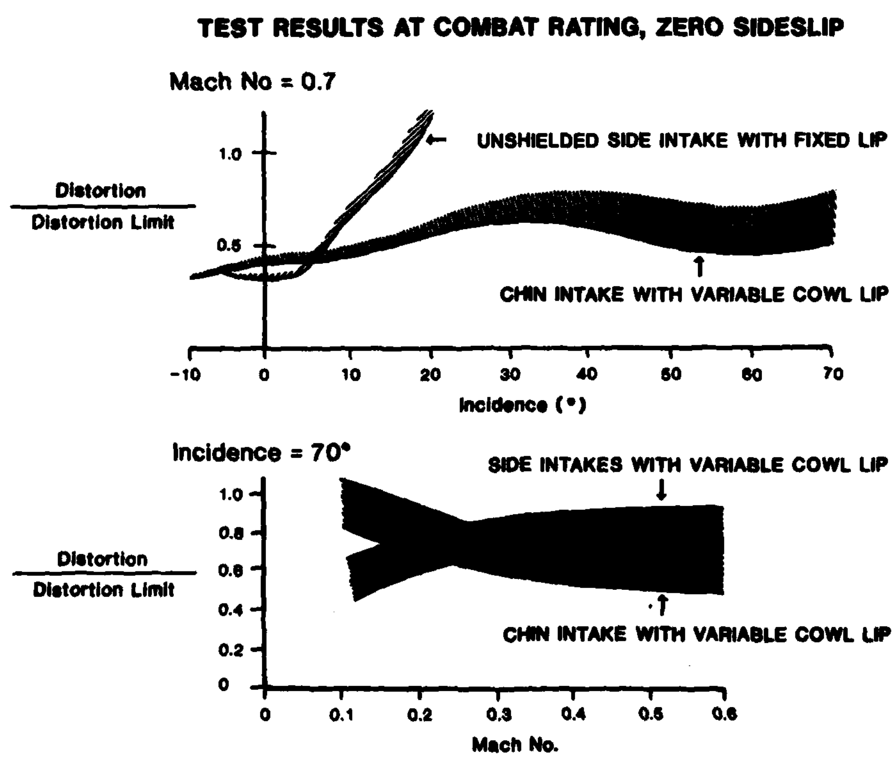

Figure 12 Time-variant intake distortion

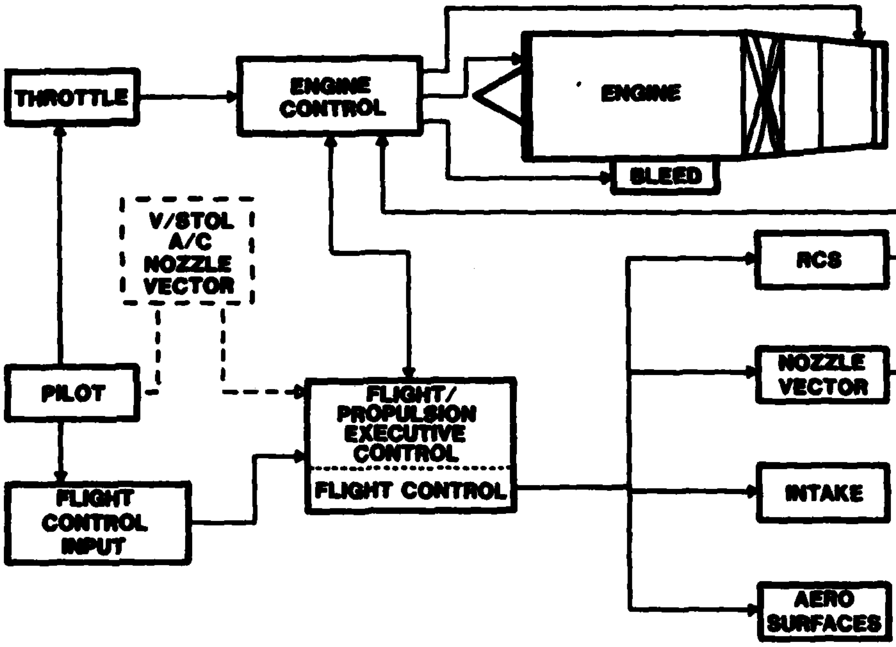

Figure 13 Flight/propulsion control system integration

- **NOZZLES**
  - Vectoring Concept
  - Sealing
  - Actuation
  - Nozzle/Engine Mounting
  - Integration
  - Materials
- **REACTION CONTROLS**
  - Engine Cycle Optimization
  - Thrust Multipliers
  - Air Bleed Source Studies
- **ACTUATION/CONTROL**
  - Flight/Engine System Integration
  - High Response Actuators
  - System Reliability
- **INTAKES**
  - Integration
  - Variable Geometry for High Incidence Performance

Figure 14 Propulsion system technologies

AD-P005 617

X-29 INTEGRATING ADVANCED TECHNOLOGIES FOR TOMORROW'S AIR COMBAT

by

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SUMMARY

The X-29 Advanced Technology Demonstrator Program is underway and in flight status at NASA Dryden Flight Research Facility. The joint US Air Force, NASA, DARPA, Grumman Aerospace Corporation program is demonstrating a set of advanced airframe technologies for consideration by designers of tomorrows combat aircraft. These technologies are described and preliminary quantitative results are discussed. These technologies are, furthermore, integrated within the X-29 airframe. Tomorrows combat aircraft will require new, integrated technologies and will benefit from the X-29 integration experience base. The X-29 aircraft is being considered for several potential "test bed" demonstrations of new equipment and airframe concepts and will serve well in this role to satisfy near term requirements.

INTRODUCTION

The subject of this conference deals with new flight control technology for air combat performance improvement. The Air Force/NASA/DARPA X-29 Advanced Technology Demonstrator Program is developing and flight demonstrating several advanced airframe technologies for tomorrow's fighters. It is useful to categorize these technologies into three major groups; (a) individual technologies (such as close-coupled canards or three-surface control), (b) integrated technologies (aeroservoelastic coupling, combination of individual technologies, high AOA, etc.), and (c) potential flight systems technologies (including gaseous oxygen/JP Emergency Power Unit, jump-strut, integrated wheel brake control and others). The current paper concentrates primarily on current or bugeted technology development within these groups followed by a brief projection of options for future consideration.

INDIVIDUAL TECHNOLOGIES

It is worthwhile reviewing briefly what specific technologies are onboard the X-29 and what has been learned thus far through flight test and wind tunnel to flight correlation. Figure 1 shows the highly instrumented X-29 in flight test at the NASA Dryden Flight Research Facility at Edwards AFB, CA. Figure 2 lists and describes the individual technologies on board and their payoffs. As of this writing, 39 successful flights have been completed for a total of 46 flight hours. Figure 3 is a summary of test points reached. A summary of information obtained from data reduced thus far, broken out by individual technology, appears in Table 1. While still in early stages of envelope expansion and flight research data gathering, it is now apparent that predictions in the aerodynamic, structures and flight controls disciplines are being met or exceeded by flight results. When completed, it is expected that these results will basically corroborate the benefits or payoff of the individual technologies and demonstrate their viability for use on tomorrow's combat aircraft. It will remain to update flying and handling qualities criteria, factor results into analysis and design codes, and conduct appropriate design studies including operational utility analyses to fully transition these flight validated technologies.

INTEGRATED TECHNOLOGIES

While made up of several advanced technologies, the X-29 was designed to develop and integrate technologies for tomorrows fighters. It has been stated that technology integration is a technology in itself. This has clearly been the case for the X-29. The most notable of these to date has been the technology developed in solving the aeroservoelastic (ASE) coupling problem encountered during fabrication. The problem presented itself as a predicted drastic reduction in flight control system gain and phase margin in the design portion of the flight envelope (Figure 4) when operating in the analog reversion backup mode. The genesis of the problem was a combination of (a) high relaxed longitudinal static stability (b) fixed gain (ie "simple") analog reversion mode (c) flexible fuselage (d) higher order dynamics effects of the limited band width actuators. The problem threatened to constrain the available flight envelope to unacceptable limits. The solution basically involved the introduction of notch filters and gain scheduling (computer hardware mods, Fig 5). Programmatically, it was necessary to provide an initial flight control system capable of stable flight in a limited envelope. In parallel, the full envelope system was completed and installed on the aircraft after the 20th flight within the limited envelope.

During the development of the X-29, an ASE model was prepared. It is now being validated with flight test results. It should be considered as an "input/output" tool for use in validating other ASE prediction/design methods. Such an approach can ward off ASE problems early in the design process. A logical extrapolation would then be to exploit ASE coupling to allow more flexible lighter advanced composite structure with aeroelastic modes controlled by the flight control system.

To understand the complex issues of technology synergisms brought about by proper incorporation of individual technology elements, a few examples are given. Figure 6a depicts the basic tendency of the forward swept wing to exhibit a reverse stall progression (root to tip) as opposed to the normal tip to root behavior of aft swept wings. Both cases would result in pitch-up tendencies. By placing a full authority canard ahead of the wing root region (Figure 6b), the FSW configuration avoids pitch-up and achieves delayed stall providing full utilization of the inboard, large lift contributing portions of the wing to high angles-of-attack. Lateral control can then be maintained with simple (light weight) tip region located ailerons. By further integrating negative subsonic static margin and nearly neutral supersonic static margin, positive lift to trim can be maintained over the entire envelope. Then, by further introduction of variable camber and three-surface control, airframe drag can be minimized.

As a second example, consider the synergism resulting from incorporation of supercritical airfoil sections with forward swept wings. Figure 7a depicts both a conventional and typical, aft loaded supercritical airfoil section for identical lift. The terminal shock is reduced in strength and is shifted toward the trailing edge. Now, note in Figure 7b, that an aft swept wing application results in an unsweeping of the terminal shock increasing its strength whereas a forward swept wing application increases shock sweep further reducing its strength. Thus the synergism of shock strength reduction by supercritical, forward swept wings results in substantial wave drag reduction. Furthermore, with reference to Figure 7b where structural sweep (quarter chord) has been kept the same, the FSW has reduced leading edge sweep. For identical leading edge pressure recovery (leading edge suction) greater leading edge thrust is attainable on the FSW. Any supersonic bluntness drag penalty for reduced leading edge sweep can be offset by maintaining small leading edge radius or deploying leading edge variable geometry devices. Corresponding weight reduction benefits can be realized if shock sweep is held fixed and FSW structural sweep reduced.

A third example of synergistic advantage is the combined application of a full authority canard with negative static margin. As previously mentioned, the canard can share lift and load with the wing yielding positive lift to trim and a combined canard and wing maneuver span load that is nearly elliptical. This of course assumes that an elliptic span wise load distribution is optimum. Reference 1 points out that for a specified wing weight, an elliptic loading is not exactly optimum and a distribution more like shown in Figure 8a would produce a lower level of induced drag. It is also observed in Figure 8b that FSW load distributions for essentially planar wings approaches this flattened optimum distribution result whereas some twist would be required on ASW. In the case of the X-29 vehicle, instability is primarily due to the canard, the wing body being nearly neutrally stable. This keeps the required canard surface rates and actuator power requirements low. Yet another example addresses the combined benefits of variable camber with forward sweep. In addition to the obvious benefits of variable wing camber, the FSW with its reduced twist requirement allows a simpler, lighter actuation system.

As indicated, the X-29 utilizes three surfaces for longitudinal control and trim. Initially designed to augment canard authority for take off and landing only, the strake flaps are utilized full time, in combination with the variable camber system to fine tune the optimum canard position throughout the Mach and AOA range of the aircraft. The incorporation of three surfaces with static instability is clearly revealed. The effects of this integration have been noted already in level accelerations of the X-29 which exhibits a much smaller deck angle variation than T-38 chase aircraft.

These technologies and their individual and integrated benefits, while promising substantial combat performance improvements, do not come without complex issues in their quantification through flight test. Thus one is faced with assigning credit for measured drag reduction to the individual and combined technologies in a non obvious way. One approach will be through ground flight correlation where analysis and wind tunnel test methods can examine individual effects and contributions towards total drag. Another approach, already in early implementation, is through employment of the Manual Camber Control (MCC) mode. The flaperon position is fixed for a given flight test condition and (except for safety override) the canard and strake flap provide the only pitch control and trim. Other approaches may include frequency response techniques, using the Remote Augmented Vehicle (RAV) ground command system to provide precise, programmed stick commands for a series of carefully controlled and repeatable maneuvers .

Turning to X-29 technology integration for high AOA research, it is apparent from foregoing arguments that the X-29 vehicle exhibits important features making it suitable for addressing this flight regime. Figure 9 depicts stabilized AOA capability for the X-29. A 70 deg upper limit has been identified for the current vehicle based on observed departure tendencies on fixed surface models. Free flight test on a 16% scale model conducted at NASA LaRC show that the vehicle is equipped with pitch and yaw vectoring is capable of greater sustained AOA, however. Control power comparisons are presented in Figure 10 indicating adequate pitch and roll control through 70 and adequate directional control to 40 deg AOA on the current configuration (Direct side force or yaw vectoring would be required to augument directional control for all axes maneuvering above 40 deg AOA).

AIR FORCE FOLLOW-ON PROGRAM

An extension of the original DARPA X-29 Program has been initiated. The No. 2 aircraft is being outfitted with a spin recovery chute and a modified instrumentation system and will be transferred to the NASA Dryden Flight Research Facility to explore the high angle of attack flight regime in 1987. Basic objectives and plans are depicted in Figure 11. Payoffs are shown in Figure 12. As shown, the bulk of the program will consist of flights up to 40 AOA. Some of these flights will involve initiation at the design Mach number (0.9) and 35,000. A simulated air combat maneuver will be commanded and as speed bleeds off during transition, a high AOA attitude will be attained. Subsequent control capability of the aircraft will be exercised and documented.

Air combat benefits for a vehicle capable of maintaining high levels of control authority at high AOA (post stall regime) are well known. Considerable international attention is being given to the means for attaining this capability without compromising other performance features. Undoubtedly some form of thrust vectoring will be required. The X-29 program does not now incorporate plans to employ thrust vectoring. Studies (Ref 2) have identified several additional benefits of pitch vectoring although as seen in Fig 10, the unaugumented vehicle has substantial pitch control authority. Common to all contemporary fighter aircraft, the X-29 runs out of directional control authority at about AOA = 40. Yaw vectoring, implemented with yaw vanes in a manner similar to that being developed for the NASA HARV (F-18) Program could be employed to give the X-29 adequate directional control power. Wind tunnel tests conducted at NASA Langley on a 16% scale model of the X-29 equipped with these yaw vanes show that the simple type of yaw vectoring provides substantial directional control authority.

Although currently limited by directional control authority to 40 deg AOA for all axes maneuvering and to 70 deg for symmetric pull-up maneuvers, the X-29 can provide definitive answers to critical post-stall maneuver questions. Fig 11 includes representative maneuver envelopes depicting initialization at the design (combat) Mach number (0.9) and transitioning rapidly to a high AOA maneuver. This type of testing, planned to begin in mid 1987 will allow extensive evaluation of the contribution of X-29 integrated technologies to this new combat arena. Other ongoing or planned flight test programs will provide additional information toward answering critical post-stall maneuver (supermaneuver) issues. Table 2 summarizes these anticipated contributions. Clearly, no single program can answer all the questions but a well coordinated, combined program will provide near term information to guide supermaneuver planning.

FLIGHT SYSTEMS TECHNOLOGIES

This final section addresses several new subsystem concepts for potential X-29 Program consideration. These include gaseous oxygen/JP fuel powered Emergency Power Unit (GOX/JP EPU) and the jump strut.

GOX/JP EPU

The X-29 currently utilizes an F-16 hydrazine fueled emergency power unit. Because of space limitations, the hydrazine supply tank was reduced in volume providing about 7 minutes of emergency power. It would be highly desireable, therefore, to convert to the GOX/JP system, promising closer to 15 min. Such a system has been receiving AF attention as an eventual substitute for the highly troublesome hydrazine system. Possible applications include F-16 EPU changeout and transition of the concept to include autonomous auxiliary power for future or existing aircraft. Breadboard tests show that the system is viable with a high promise of improved reliability and maintainability. Design studies show that a GOX/JP system could be incorporated readily into the X-29.

JUMP-STRUT

The jumpstrut, as the name implies, uses an on-board stored energy source to activate either the nose or main landing gear (or both) strut extensions to achieve augmented takeoff power. Dramatic reduction in takeoff speed and ground roll appear possible with this light weight, low cost concept. Recent Navy high speed taxi tests using a jump nose gear only installed on a T-38 aircraft, show substantial reductions in take off speed. Advantages of jump-strut over other technologies such as "ski-jump" include system autonomy, cross wind tolerance, programmable jump profiles etc. Current Navy interest is in reducing dependency on carrier based catapault systems as well as in providing aborted landing recovery.

In separate development programs, F-16 main landing gear will be equipped with jump capability for eventual F-16 application. As it happens, the X-29 uses an F-5 or T-38 type nose gear and F-16 main gear thus making it a suitable test platform for this high performance/payoff technology.

CONCLUSIONS

The X-29 aircraft has met or significantly exceeded all performance expectations. It will develop and integrate several advanced aircraft technologies for near term exploitation in combat aircraft. It will serve as a long term demonstrator of on board as well as newly emerging technologies and subsystems.

REFERENCES

1. G. Lobert, "Spanwise Lift Distribution of Forward and Aft Swept Wings in Comparison to the Optimum Distribution Form", Journal of Aircraft, V18 June 1981.
2. E.H. Miller "Performance of a Forward Swept Wing Flight Utilizing Thrust Vectoring", AIAA preprint 83-2482, Oct 1983.

3. G. Uhuad, T. Weeks, R. Large, "Wind Tunnel Investigation of the Transonic Aerodynamic Characteristics of Forward Swept Wings", Journal of Aircraft, V20 March 1983.

Program	Contribution
FSW	- No adverse damping trends noted - Good correlation with predicted bend-twist characteristics - No aeroservoelastic anomalies
Close coupled canards	- Low levels of structural acceleration observed - Canard activity small
FCS	- No anomalies reported in-flight - Longitudinal trim attained automatically - Minor transients during mode switching - Adequate gain and phase margin maintained
Flaperon system	- Some link loads approaching criteria limits
Three-surface control	- Relative deck angle reduction - Near constant drag during pushover-pull ups
Aggregate	- Gust response results in linear translation without significant load factor change - Excessive control stick motion required in gunsight tracking (lateral) - Drag significantly lower than predicted through M=.9 - Subsystems performance exceptional; multiple flights/day (3 so far); one in-flight equipment failure in 13 months (AHRS) - Aircraft handles better than simulator prediction

Table 1 - Data Summary by Technology

Program	Contribution
F-18 HARV	Thrust Vectoring Control laws (include engine)
F-15 STOL	Thrust Vectoring/Reversing Aero/propulsive control integration
X-29 Hi AOA	High pitch rate Negative static stability Control laws Forward swept wing Large trim AOA

Table 2 - Existing or near term flight test programs contributing to supermaneuver.

Fig. 1 X-29 In Flight Test at
NASA Dryden Flight Research Facility

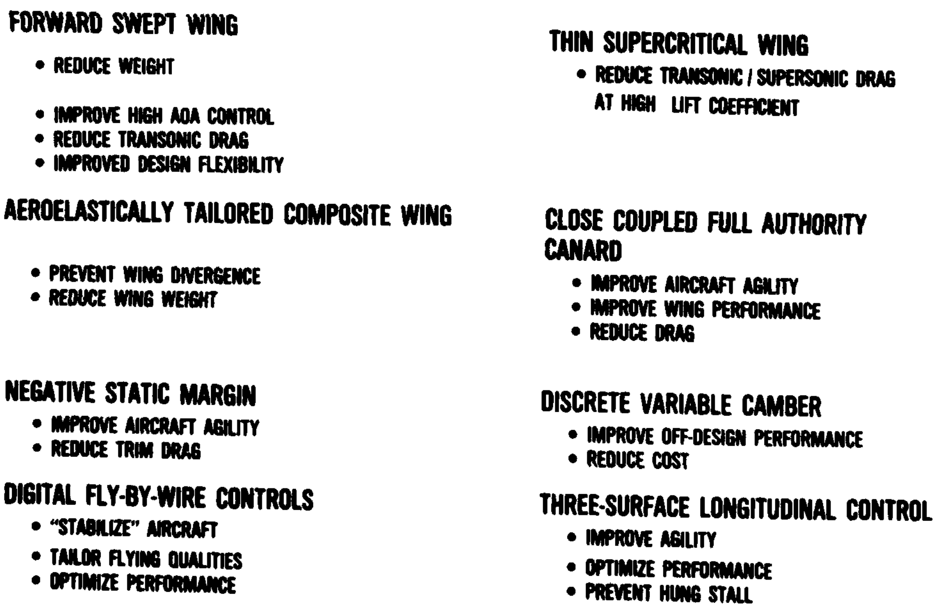
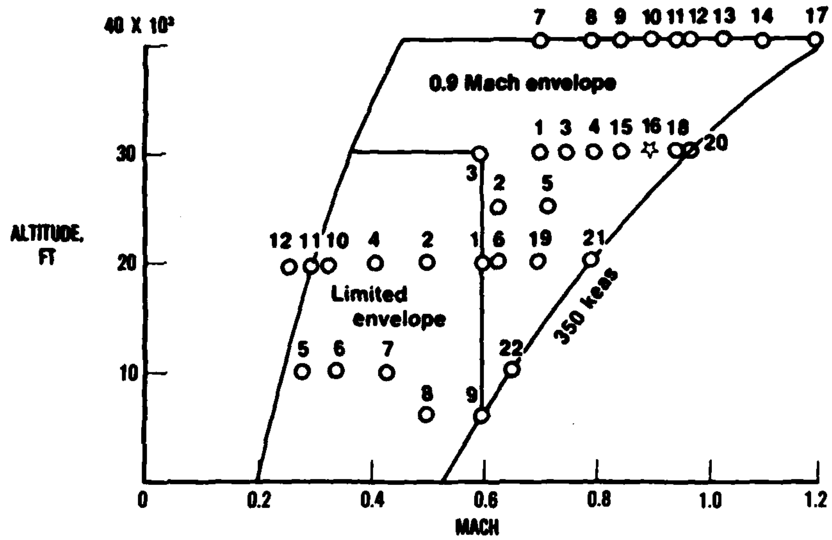


Fig. 2 X-29 Technologies and Payoffs



(a) Flight test point summary

INTEGRATED TEST BLOCK 1

- **DISCIPLINES:**
  - DYNAMICS, AERO, FCS
- **TESTS:**
  - STATIC RAPS
  - AIRSPEED / ADA CALIBRATION
  - DOUBLETS
  - FREQUENCY SWEEPS

INTEGRATED TEST BLOCK 2

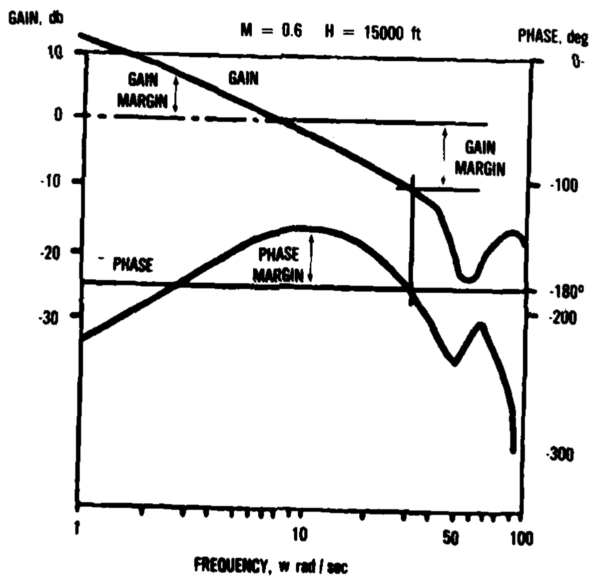
- **DISCIPLINES:**
  - FCS, AERO, PERFORMANCE / PROPULSION, LOADS
- **TESTS:**
  - TRIM SHOT
  - STEADY HEADING SIDESLIP
  - STEP INPUTS
  - ROLLS: 45-45, 60-60, 360°
  - THROTTLE TRANSIENTS
  - PUSH OVER - PULL UP
  - WINDUP TURN (CONST ALT., CONST. MACH)

EXTENDED MANEUVERS

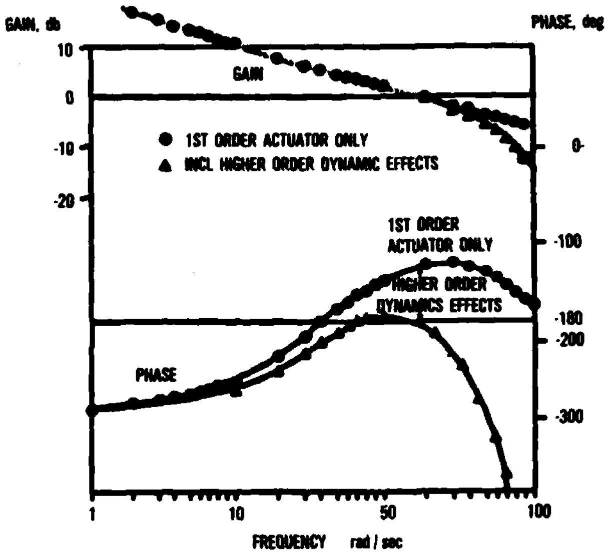
- **DISCIPLINES:**
  - AERO PERF
- **TESTS:**
  - ELEVATED G DOUBLETS
  - ELEVATED G SIDESLIPS
  - ELEVATED G ROLLS
  - BUFFET WINDUP TURNS
  - STEADY THRUST LIMITED TURNS
  - CONST AOA TURNS
  - 1 G ACCEL / DECEL
  - ELEVATED G ACCEL / DECEL
  - PERFORMANCE CLIMBS
  - THROTTLE TRANSIENTS IN WIND-UP TURNS
  - ENGINE SAWTOOTH CLIMBS
- **DISCIPLINE:**
  - LOADS
- **TEST:**
  - ABRUPT PULLUP / PUSHOVER
  - TURN REVERSAL
  - RUDDER KICK
  - RUDDER REVERSAL
- **DISCIPLINE:**
  - HANDLING QUALITIES
- **TEST:**
  - COOPER-HARPER FORMATION EVAL.
  - AIR TO AIR TRACKING

(b) Flight test details

Fig 3 Current flight test program



(a) Open loop frequency response, longitudinal control system



(b) Impact of higher order dynamics

Fig 4 X-29 Gain and phase margin details

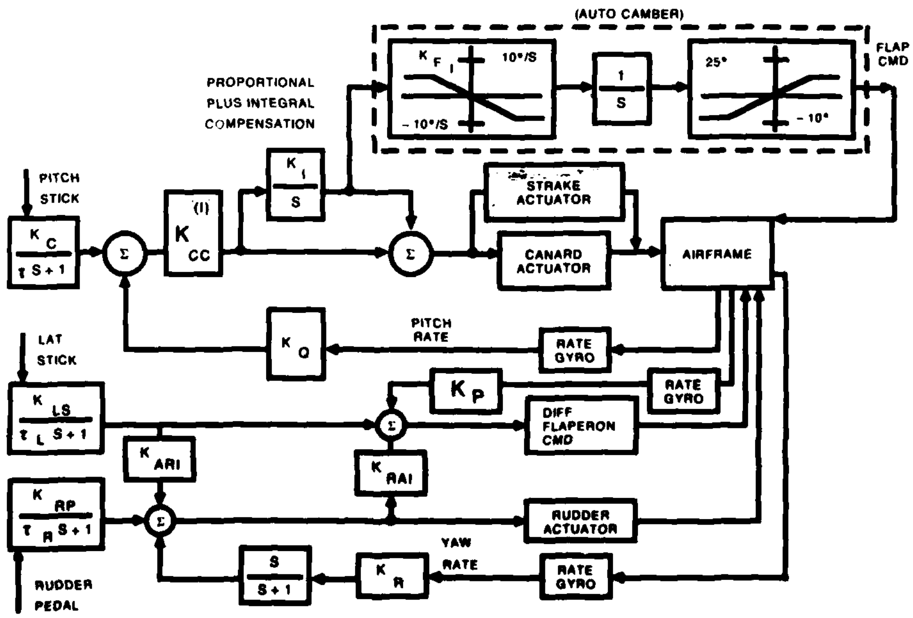
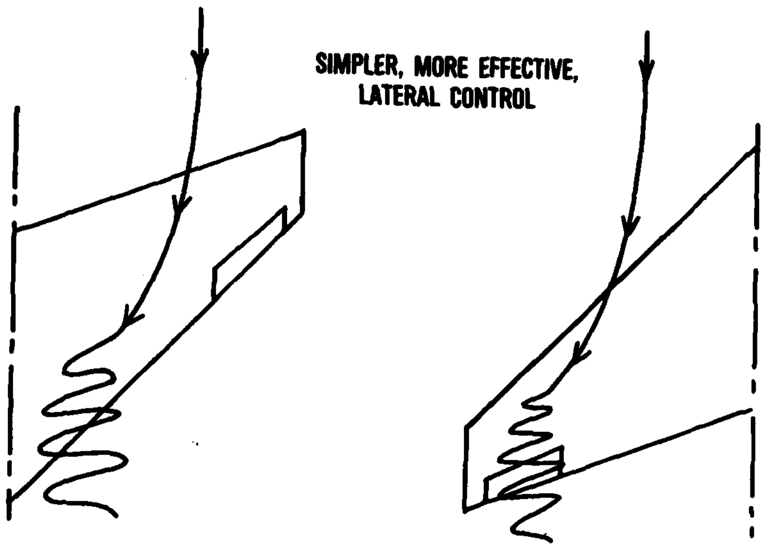
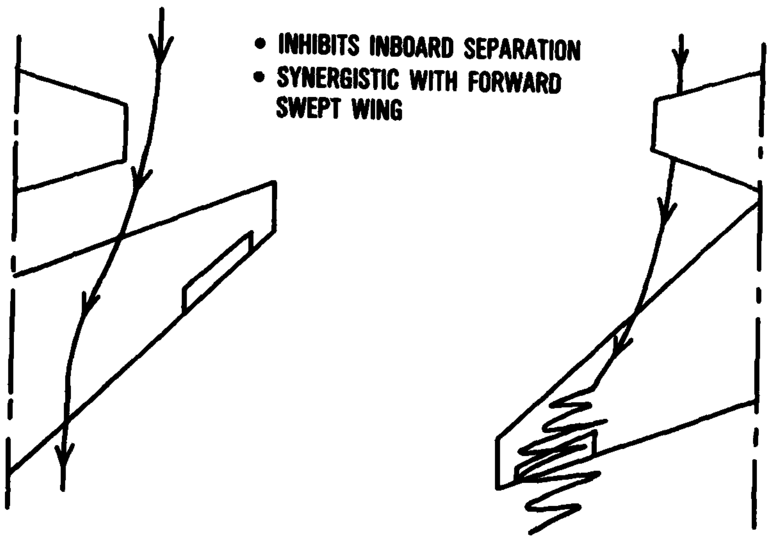


Fig. 5 changes to original Analog Reversion mode

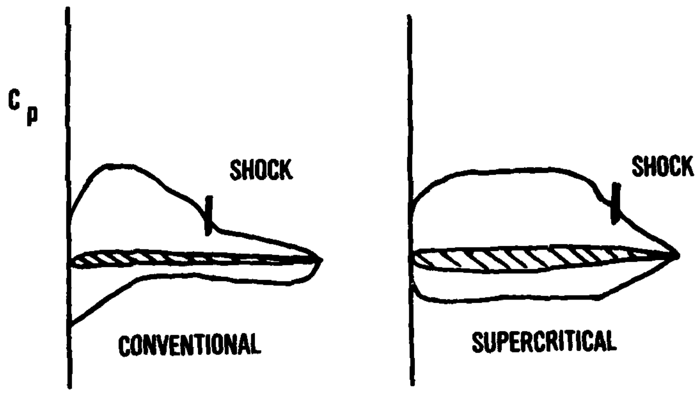


(a) Reverse stall progression results in FSW delayed tip stall



(b) Adding a close coupled canard delays root stall

Fig 6 FSW stall progression compared with ASW



(a) Supercritical sections result in aft shock location

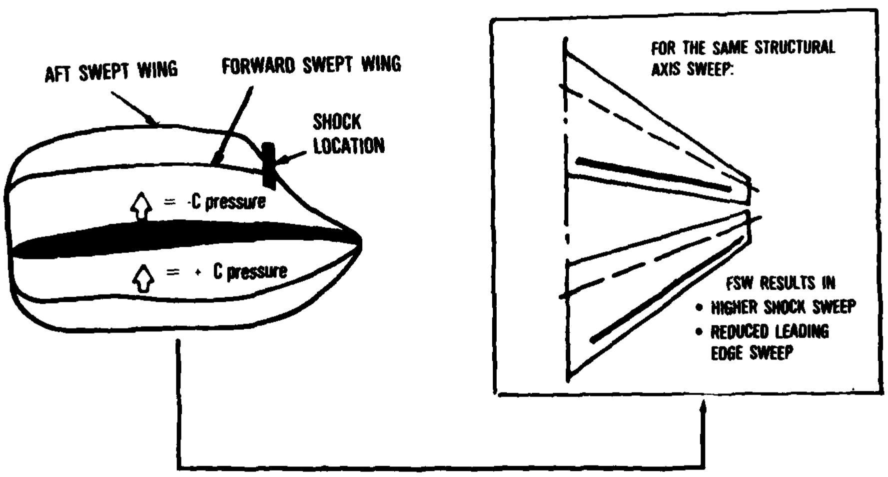


Fig. 7 Transonic benefits of FSW

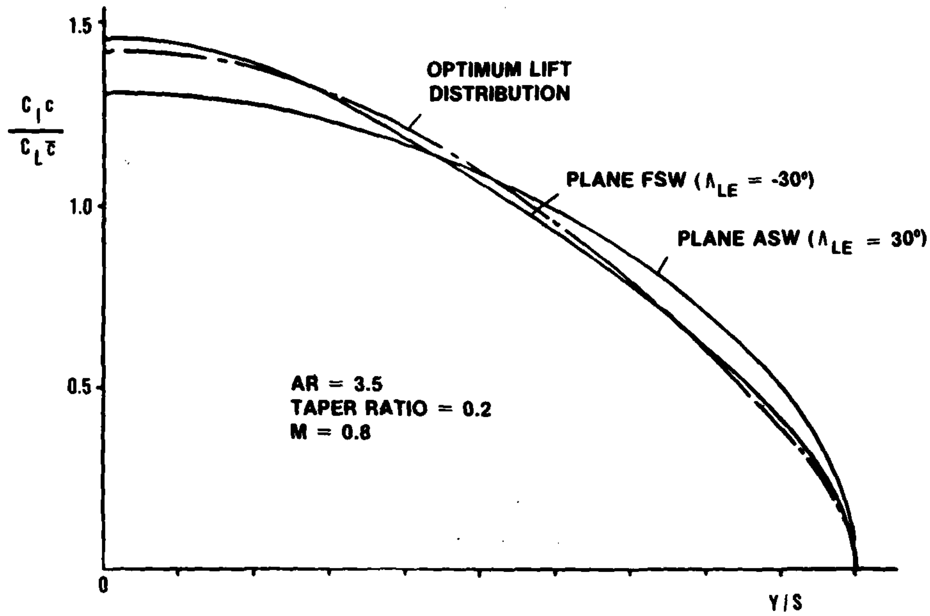


Fig. 8 Spanwise Load Distribution Comparison from REF 1. Optimum Load Distribution Based on Equal Area, Equal Weight Wings

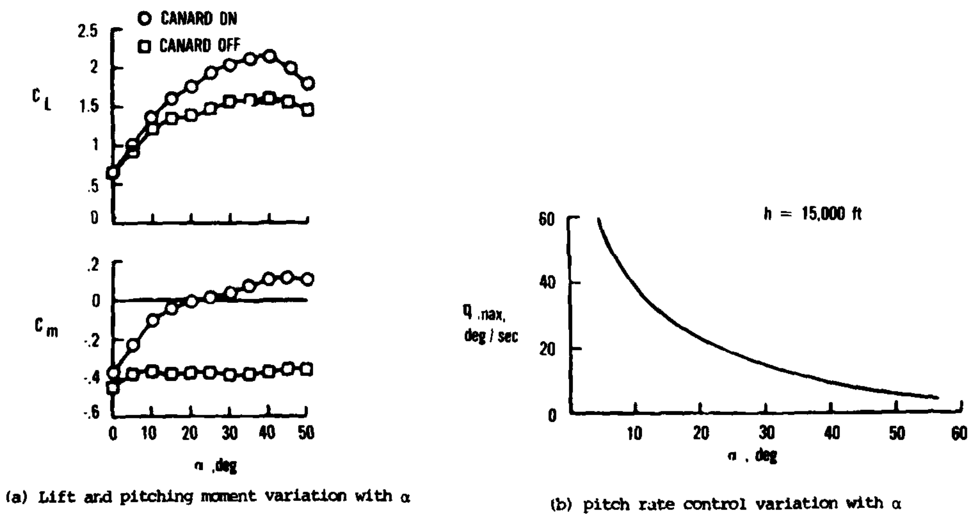


Fig 9 stabilized AOA capability of the X-29

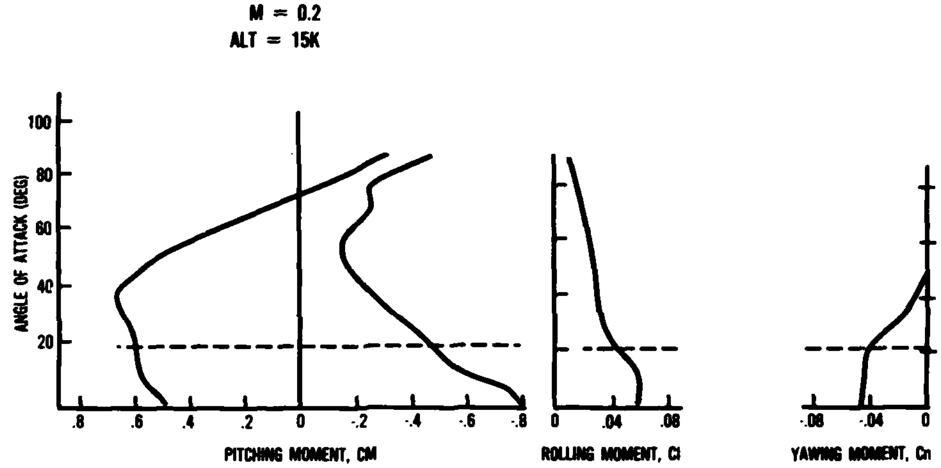
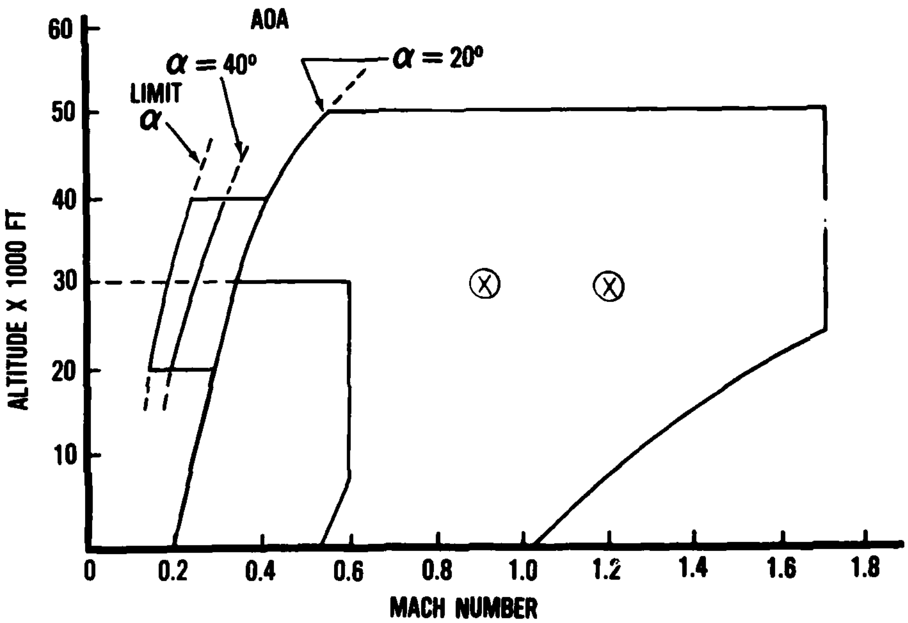


Fig. 10 X-29 Unaugmented Control Power at High Angle-of-Attack



OBJECTIVES:

- HIGH AOA
  - MANEUVER TO 40° AOA - ALL AXES
  - MANEUVER TO LIMIT AOA - PITCH ONLY
- EXPANDED RESEARCH
  - CONTINUE TEST TO FULLY UNDERSTAND X-29 ADVANCED TECHNOLOGIES
  - AIRFRAME AVAILABLE FOR OTHER PROGRAMS

FLIGHT TEST

- HIGH AOA
  - 5 FUNCTIONAL FLIGHTS
  - 60 FLIGHTS UP TO 40° AOA
  - 15 FLIGHTS TO ACHIEVE LIMIT AOA
  - MOST TESTING AT 35 TO 40K ALTITUDE
- EXPANDED RESEARCH
  - UP TO 2 FLIGHTS / WEEK
  - DEPENDENT ON RESEARCH REQUIREMENTS ENGINEERING SUPPORT

Fig. 11 X-29 Follow-on Flight Test Program

- **HIGH ANGLE OF ATTACK**
  - FORWARD SWEPT WING-PROVE / DISPROVE UNIQUE ADVANTAGES
  - GENERIC FIGHTER
    - UNDERSTAND CLOSE COUPLED CANARD APPLICATIONS FOR IMPROVED MANEUVERING
    - DEVELOP UNDERSTANDING OF "WING ROCK" PHENOMENA AND METHODS FOR CONTROL
    - DEVELOP AND VALIDATE PREDICTION / EVALUATION CRITERIA
    - UNDERSTAND IMPLICATIONS OF STATIC INSTABILITY ON AGILITY
- **EXPANDED FORWARD SWEPT WING RESEARCH**
  - FULLY UNDERSTAND X-29 ADVANCED TECHNOLOGIES AND IMPLICATIONS ON:
    - AERODYNAMICS
    - STRUCTURES
    - CONTROLS
    - FUTURE MILITARY SYSTEMS
  - POTENTIAL USE OF AIRFRAME AS TEST BED FOR "PIGGYBACK" EXPERIMENTS

Fig. 12 Follow-on Program Payoffs

SIMULATION D'UN SYSTEME INTEGRE DE COMMANDES DE VOL ET DE CONDUITE DE TIR CANON AIR-SOL

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BP 72 92322 CHATILLON CEDEX

RESUME

Une étude de simulation au simulateur de l'ONERA a démontré qu'un système intégré de commandes de vol et de conduite de tir (IFFC) réduit de manière significative la charge de travail du pilote pendant la phase de tir canon air-sol, et améliore les qualités de vol de l'avion par rapport à celles d'un avion conventionnel. Le système IFFC a été étudié dans le but d'utiliser uniquement l'instrumentation embarquée classique, à l'exclusion de capteurs évolués (de type électro-optique par exemple). Une étude préliminaire des forces directes latérales a montré qu'elles n'apportent pas une amélioration très significative dans l'efficacité de la visée.

ABSTRACT

A fixed base simulation study conducted at ONERA demonstrated that an IFFC system decreased pilot workload during an air-to-ground gunnery attack and improved airplane flying qualities in comparison with those of a conventional aircraft. The IFFC system was designed to use only standard on-board instrumentation, excluding sophisticated sensors (e.g electro-optical). A preliminary investigation of direct side force showed that it does not provide significant improvements in aiming effectiveness.

1. INTRODUCTION

Parmi les tâches de pilotage, le tir air-sol est l'une des plus difficiles en raison du temps très court imparti pour la visée et des dangers présentés par la proximité du sol et la défense anti-aérienne adverse. Le résultat dépend du fonctionnement de la chaîne pilote-loi de commande-avion-conduite de tir-arme-munition. On examinera dans la suite l'influence de la conduite de tir et plus particulièrement celle de la loi de commande.

Sur les viseurs rustiques, la hausse est affichée manuellement par le pilote. Elle est calculée à partir de tables de tir pour des conditions de tir bien déterminées : distance, incidence, vitesse, pente, dérapage nul, inclinaison nulle. Ces conditions doivent être respectées si le pilote veut faire une visée correcte. L'apparition des conduites de tir plus évoluées pour le tir air-sol a permis d'étendre les conditions de tir : distances, vitesses et pentes variées. Certaines conduites de tir tiennent également compte du dérapage pour la correction tireur et de l'inclinaison pour la correction de gravité. On distingue globalement deux modes de fonctionnement d'une conduite de tir air-sol : mode CCPL (Calcul Continu du Point de Largage) pour le bombardement ; mode CCPI (Calcul Continu du Point d'Impact) pour le tir canon ou le bombardement. La hausse devient mobile, ce qui a priori ne facilite pas la tâche du pilote puisqu'il doit amener en coincidence dans le viseur deux points mobiles, cible et réticule de tir.

Le niveau des qualités de vol en tir air-sol reste jusqu'à présent très moyen. La tendance générale est l'utilisation d'une boucle interne d'augmentation de la stabilité <u>unique</u> pour le tir de tous les types d'armes prévus sur l'avion, le réglage des gains résultant d'un compromis entre ces différents modes. L'amélioration de l'efficacité du tir grâce à l'amélioration des qualités de vol a déjà fait l'objet d'études menées aux Etats-Unis plus particulièrement [1,2], parmi lesquelles :

- le programme TWead (Tactical Weapon Delivery) ; l'autorité limitée du système d'augmentation de la stabilité (SAS) d'un F-4 fut remplacée par un système de commande augmenté (CAS) à gain élevé.

- Le programme Multimode Control ; la loi de commande d'un A-7 fut adaptée au type d'arme utilisé : mode pente FP (Flight Path) pour le bombardement, mode attitude PA (Precision Attitude) pour le tir canon.

- le programme AFTI (Advanced Fighter Technology Integrator) ; des degrés de liberté supplémentaires du mouvement d'un F-16 furent exploités grâce à l'adjonction de gouvernes de forces directes.

Par ailleurs, le programme IFFC (Integration of Flight and Fire Control) [3] a montré récemment l'intérêt d'une commande automatique de vol pour la visée fine, ceci grâce à la mise au point de capteurs électro-optiques évolués.

L'objet de cette communication est de présenter une étude entreprise à l'ONERA depuis 1979 [4] concernant un système intégré de commandes de vol et de conduite de tir (IFFC) pour le tir canon air-sol. L'approche adoptée sera décrite et des résultats de simulation au sol seront donnés. L'amélioration par rapport à une loi de commande conventionnelle sera discutée. L'intérêt d'une gouverne de force directe latérale sera examiné.

2. SYSTEME INTEGRE DE COMMANDES DE VOL ET DE CONDUITE DE TIR

Pour assurer le pilotage d'un avion, il est tout à fait envisageable de commander des variables directement associées à son mouvement. Ce mode, dit de "pilotage par objectif" (PO) simplifie l'exécution de certaines manoeuvres exigeant une action coordonnée sur les gouvernes, tâche autrement difficile si elle est confiée au pilote. Des études de PO faites à l'ONERA ont permis ainsi d'établir des lois de braquage des gouvernes appropriées à la commande des variables d'état du mouvement (dérapage, vitesses de roulis, tangage, lacet,...). Les essais sur simulateur avec pilote humain dans la boucle ont mis en évidence la pilotabilité de telles lois ainsi que les qualités de vol améliorées qu'elles confèrent à l'avion.

Pour améliorer le pilotage de l'avion dans la phase de tir air-sol, il a été proposé de mettre à la disposition du pilote des variables de commande directement associées à la visée, en l'occurence la position du point d'impact des obus au sol. Un tel système de commande devrait réduire de façon significative la charge de travail du pilote et augmenterait la précision de la visée. Ce concept, illustré sur la Figure 1, a été validé au simulateur du Centre d'Essais en Vol d'Istres [5]. Une architecture du système de commande a été présentée dans la Référence [6] ainsi que la formulation mathématique de la loi de commande. Le système intègre une conduite de tir, un régulateur de tir et un régulateur de pilotage (Figure 2).

Conduite de tir (CCPI classique)

Le point d'impact (PI) instantané des obus au sol est calculé à partir des mesures de distance, d'incidence, de dérapage et des variables d'attitude de l'avion. Le PI est matérialisé au pilote par le réticule de tir. La conduite de tir lui fournit aussi une indication sur le déplacement prévisible du PI en fonction des évolutions de l'avion. L'utilisation d'une conduite de tir permet essentiellement d'augmenter la fenêtre de tir.

Architecture du système de commande

Actuellement, grâce à l'utilisation de calculateurs numériques, il est tout à fait envisageable que des changements de lois de commande au travers d'un commutateur de mode de pilotage permettent de modifier les qualités de vol de sorte à optimiser l'avion, plus le système de commande, pour des tâches spécifiques. Cette possibilité n'est pas tout à fait nouvelle puisque les pilotes automatiques permettaient déjà de réaliser des objectifs précis dans certaines phases de vol. Une des difficultés rencontrées est la limitation de l'effet des transitoires au moment de la commutation entre les différents modes. L'architecture du système de commande présentée sur la Figure 2 permet de limiter ces transitoires. Elle ne nécessite par ailleurs pas de modification importante du système de commande de base de l'avion (régulateur de pilotage). Les objectifs de pilotage choisis ici pour ce régulateur sont des consignes de vitesses angulaires de l'avion (roulis, tangage, lacet). Le régulateur fournit en sortie les ordres de braquage nécessaires des gouvernes. Le rôle du régulateur de tir, placé en amont, est d'élaborer des consignes de vitesses angulaires de l'avion correspondant à une vitesse de rotation de la ligne de visée commandée par le pilote.

Lois de commande

Une formulation mathématique détaillée des lois du régulateur de tir et du régulateur de pilotage a été présentée dans la Référence [6] . On rappelle seulement que ces lois sont non-linéaires et assurent un découplage algébrique strict des différentes paires d'entrées-sorties [7] . Ainsi, les non-linéarités de la cinématique de la ligne de visée d'une part, de la dynamique de l'avion d'autre part sont éliminées algébriquement par ces lois. Une des conséquences est que le pilotage de la ligne de visée est pur et découplé quelle que soit l'inclinaison de l'avion.

Modes de pilotage

Le concept de pilotage du PI illustré sur la Figure 1 peut donner lieu à plusieurs modes de pilotage. La manière de piloter chacun de ces modes au moyen des organes de pilotage classiques (manche, palonnier) ou moins classiques (joystick) peut faire à elle seule l'objet d'une étude approfondie. On sait cependant qu'on ne peut pas attendre du pilote qu'il actionne simultanément plusieurs commandes, il est donc nécessaire de réduire sa tâche à des proportions raisonnables. De même, la dissimilarité du mode nouveau de pilotage par rapport au mode de pilotage conventionnel doit rester acceptable pour le pilote. Trois modes associés au concept du pilotage du PI sont illustrés sur la Figure 3 :

- mode 1 : le déplacement du PI est commandé dans les axes liés à l'avion. Le manche en profondeur commande une vitesse de déplacement dans le plan de symétrie de l'avion, le manche en gauchissement commande une vitesse de déplacement dans un plan perpendiculaire au plan de symétrie, ainsi qu'un angle de gîte désiré lorsque le déplacement devient important. Le palonnier n'est pas utilisé.

- mode 2 : même principe que précédemment mais le déplacement du PI est commandé dans les axes liés au sol.

- mode 3 : déplacement du PI commandé dans les axes avion par le manche en profondeur et le palonnier. Le manche en gauchissement commande une vitesse de roulis.

Des essais préliminaires au simulateur du CEV d'Istres [5] ont indiqué qu'une commande bien adaptée pour le tir air-sol posséderait les caractéristiques suivantes :

- acquisition initiale facile (amortissement, rapidité) avec la commande du manche, l'inclinaison pouvant être très importante.

- acquisition finale facile avec la même commande du manche, le mode d'alignement "ailes horizontales" étant particulièrement efficace.

- utilisation du palonnier non souhaitée pendant l'acquisition finale.

Les modes 1 et 2 devraient permettre de satisfaire ces exigences. Actuellement, seul le mode 1 a été essayé de manière intensive au simulateur de l'ONERA. La Figure 4 montre qne la loi d'assiette latérale de l'avion est fortement non-linéaire en fonction de la commande de gauchissement. L'inclinaison ne devient importante que pour des déplacements importants de la commande. Ainsi, l'avion s'incline du côté de la correction à effectuer, lorsque le ralliement est d'assez grande amplitude. Mais le retour vers l'assiette latérale nulle n'a pas besoin d'être commandé spécifiquement par le pilote, ce retour est assuré par le système lorsque l'écart latéral à corriger diminue. Une conséquence originale de cette disposition est que l'assiette maximale accessible en roulis doit être plafonnée. La valeur retenue est 180° pour le plein braquage du manche (Figure 4). L'avion est donc capable de vol dos, mais pas du tonneau.

3. ESSAIS DE SIMULATION

Les essais ont été effectués sur le simulateur à base fixe de l'ONERA. Le simulateur est organisé autour d'une cabine fixe, d'un système de visualisation tête haute et d'une figuration tête basse (Figure 5).

Trois modèles semblables d'avion, dérivés d'un même avion, ont été préalablement définis à des fins de comparaison (Figure 6) :

- avion XN, avec pilotage conventionnel et équipé d'un SAS ; la validation de cet avion de base a été basée sur le jugement qualitatif d'un certain nombre de pilotes qui à l'unanimité ont considéré l'avion XN comme étant représentatif d'un avion de combat moderne avec de bonnes qualités de vol.

- avion XA, avec PO du PI (mode 1)

- avion YA, avec PO du PI (mode 1) et avec gouverne de force directe latérale. L'avion YA se différencie de l'avion XA par le fait que le pilote dispose en plus d'une commande du dérapage assurée au moyen d'un joystick monté sur le manche.

Une première comparaison des apports respectifs du PO et des forces directes latérales a été faite sur des scénarios typiques de tir air-sol dont un exemple est illustré sur la Figure 7. Les essais ont été effectués pour différentes conditions de vent et de turbulence.

Les résultats sont composés d'éléments subjectifs (commentaires des pilotes) et d'éléments objectifs (examen des tracés, étude statistique).

<u>Commentaires</u>

- <u>avion XN</u> :
  . La visée est satisfaisante en présence d'une faible turbulence.
  . La visée transversale devient délicate à stabiliser lorsque la turbulence augmente. Les corrections de visée longitudinale restent faciles à exécuter mais elles sont détériorées par une charge de travail importante en latéral.
  . En présence de vent de travers, les corrections deviennent difficiles à faire, le couplage longitudinal latéral augmente notablement la charge de travail, et les résultats sont médiocres.
  . Pour un tir sur deux cibles, la 2è cible étant écartée de 100 m de la 1ère, latéralement et longitudinalement, le changement de cible par une mise en roulis de l'avion est rapide mais peu précis. L'erreur de visée restant à annuler est relativement importante et le peu de temps qui reste avant la ressource ne permet pas de faire une visée satisfaisante. Par ailleurs, le pilote peut hésiter dans le choix de la commande (manche latéral ou palonnier) pour annuler cette erreur de visée résiduelle.

- <u>avion XA</u> : la comparaison est faite avec l'avion XN.
  . Les commentaires des pilotes sont très favorables. Le pilotage devient beaucoup plus facile parce qu'il est ressenti comme plus pur et plus direct. La charge de travail est nettement diminuée, surtout dans la correction des écarts latéraux. Mais le bénéfice le plus spectaculaire est obtenu lors des ralliements, à partir d'une position 3/4 dos par exemple. Par comparaison avec l'avion XN, la manoeuvre est beaucoup plus facile, plus rapide et plus nette (Figure 8).
  . L'amélioration des conditions de tir est spectaculaire par forte turbulence, tout écart d'alignement observé pouvant être contré rapidement et stabilisé (Figure 9).

. En présence de vent de travers, le pilote trouve facilement la quantité de commande nécessaire pour contrer et ensuite agit sur la commande comme s'il n'y en avait pas. L'assiette latérale reste nulle ou faible et les corrections de visée restent faciles à effectuer. Le tir se fait le plus souvent à dérapage non nul ; le calcul du PI effectué par la conduite de tir sera donc moins précis. Il conviendra d'améliorer la précision de calcul actuelle des conduites de tir en présence de dérapage si l'on veut bénéficier des pleins avantages apportés par le PO.

. Dans la tâche de changement de cible, l'efficacité a été jugée un peu faible et le pilote veut toujours s'aider de l'inclinaison pour accélérer l'alignement initial. Les corrections finales sont faites toutefois avec des ordres faibles au manche, c'est-à-dire pendant que l'assiette latérale revient à zéro.

L'alignement "ailes horizontales" conserve donc son intérêt mais si le ralliement sur la deuxième cible est un peu lointain, la pertubation de roulis introduite par le pilote prend un temps significatif. Elle demeure toutefois très inférieure à celle rencontrée en pilotage normal.

avion YA : la comparaison est faite avec l'avion XA.

. La charge de travail est pratiquement inchangée. Comme pour l'avion XA, le pilote dose très facilement le taux de déplacement du PI.

. La réponse de l'avion à la turbulence semble moins bien amortie, mais la stabilité et la précision de la visée sont conservées.

. En présence de vent de travers, la possibilité de l'alignement "ailes horizontales" reste conservée. Le dérapage est par contre constamment nul ce qui améliore la précision du PI.

. Dans la tâche de changement de cible, l'efficacité de l'alignement "ailes horizontales" a été jugée satisfaisante, mais le gain par rapport à l'avion XA n'est pas net. Les pilotes préfèrent souvent accélérer l'alignement sur la deuxième cible par une mise en roulis pour disposer de plus de temps pour faire les corrections finales.

Etude statistique

Elle a été faite sur un certain nombre d'indices de performance (erreurs de visée, activité du pilote, facteurs de charge, ...). A titre d'exemple, la Figure 10 présente les scores simulés obtenus avec XN, XA et YA, pour trois conditions de vent et deux conditions de turbulence, et pour un scénario de tir sur deux cibles. Les scores simulés sont meilleurs dans tous les cas pour XA et YA avec un léger avantage à YA. La dispersion des résultats est relativement importante en raison du faible nombre d'essais effectués en tir sur deux cibles.

4. BOMBARDEMENT

Le principe du pilotage du PI décrit précédemment pour le tir canon air-sol s'applique sans modification importante au bombardement en mode CCPI ou CCPL. La différence réside uniquement dans le calcul du PI qui dépend, dans le cas présent, essentiellement du vecteur vitesse de l'avion.

5 - CONCLUSION

Une étude de simulation au simulateur de l'ONERA a démontré qu'un système intégré de commandes de vol et de conduite de tir (IFFC) réduit de manière significative la charge de travail du pilote pendant la phase de tir canon air-sol, et améliore les qualités de vol de l'avion par rapport à celles d'un avion conventionnel, particulièrement lorsqu'un changement de cap important est nécessaire pour acquérir la cible.

Le système IFFC a été étudié dans le but d'utiliser uniquement l'instrumentation embarquée classique, à l'exclusion de capteurs évolués, de type électro-optique par exemple.

L'architecture du système proposé ne devrait pas nécessiter de modification significative du système de commande de base de l'avion.

Une étude préliminaire des forces directes latérales a montré qu'elles n'apportent pas une amélioration très significative dans l'efficacité de la visée. Il est possible que l'augmentation d'efficacité se manifeste plus nettement dans des scénarios de tir plus finement établis que ceux qui ont été utilisés. Mais il faudra être sûr que la comparaison faite entre les configurations avec et sans force directe sera vierge de tout biais introduit par la réponse de l'avion à la turbulence.

REFERENCES

1. Quinlivan, R. and Tye, G., Multimode Flight Control for Precision Weapon Delivery. NAECON'72 Proceedings of the National Aerospace Electronics Conference, Dayton, Ohio.

2. Smith, H. and Carleton, D. Weapon Delivery Impact on Active Control Technology. AGARD Impact of Active Control Technology on Airplane Design, June 1975.

3. Huber, R.R., Integration of Flight and Fire Control. AGARD-CP272. Advances in Guidance and Control Systems using Digital Techniques, May 1979.

4. Dang Vu, B., Multivariable Aircraft Control by Maneuver Commands - An Application to Air-to-Ground Gunnery. Proceedings 12 th ICAS Congress, Munich, 12-17 October 1980.

5. La Burthe, C. et Dang Vu, B., Essais en simulation de lois de commandes actives pour le tir canon air-sol. ONERA RT n° 9/5148 SY, mars 1983.

6. Dang Vu, B. et Mercier, O.L., *Loi de commande non-linéaire pour le pilotage des avions en phase d'attaque air-sol.*
AGARD-CP 349 Integration of Fire Control, Flight Control and Propulsion Control Systems, mai 1983.

7. Mercier, O.L., Calcul de commandes non-interactives pour les systèmes linéaires et non-linéaires. ONERA NT n° 1981-6, novembre 1981.

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THE IMPACT OF FUTURE AVIONICS TECHNOLOGY ON THE CONDUCT OF AIR WARFARE

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SUMMARY

This paper presents a synopsis of the conclusions reached by the Systems Subpanel of the NATO AGARD workshop on "The Potential Impact of Developments in Electronic Technology on the Future Conduct of Air Warfare." The workshop was conducted at SHAPE Technical Center, The Hague, The Netherlands from 21 to 25 October 1985.

1. INTRODUCTION

During October 1985, sixty-five individuals (military and civilian) representing nine NATO nations, four AGARD panels, and the NATO staff, participated in a workshop at SHAPE Technical Center, The Hague, The Netherlands. The workshop was sponsored by the NATO AGARD Avionics Panel and the topic was "The Potential Impact of Developments in Electronic Technology on the Future Conduct of Air Warfare." The workshop consisted of subpanel briefings (Air Warfare, Technology, and Applications), subpanel meetings, and general discussions. The baseline for the workshop was a presentation of threat and tactics envisioned for the 2000-2010 time frame by the Air Warfare subpanel.

This paper presents a synopsis of the conclusions reached by the Systems Subpanel. The paper first describes the new technology of avionic system integration and the elements that comprise it; the functions which this new technology enables; a system design methodology; and finally, the impact of the new avionic system attributes on operation and support and the conduct of air warfare.

2. AVIONIC SYSTEM INTEGRATION TECHNOLOGY

The integration of avionic systems has evolved over the past decade to a point where it can be considered a technology in and of itself. In the context of the total aircraft system, it is an enabling technology, i.e., a technology which allows further enhancements to the system (such as automation). System integration has been recognized as a necessary first step in our evolution toward a twenty-first century aircraft system. The key elements that comprise system integration technology are processors, data communication paths, software and fault detection/fault isolation. These elements are brought together in such a way so as to provide an efficient integrated core system. The manner in which they are brought together is usually referred to as the system architecture. The following sections present a brief projection of present technology trends in the areas of system architectures, processing, data communication paths, software, and fault detection/fault isolation.

3. SYSTEM ARCHITECTURE

System Architecture can be defined as the overall design configuration with respect to the positioning of processing functions and the data path structure established between the various system and subsystem processors, the system sensors, and the system control/displays.

An important characteristic of the emerging microcircuit technology is the very natural way in which it allows a system to be modularized. Avionic systems of the future will be built up of a few types of generic digital elements (processors, memories, network interfaces, etc.). The avionic system may include very large numbers of elements of each type, but it will be possible to limit the number of different types to only a few. By properly interconnecting the elements and programming them appropriately, a broad range of functions can be supported using only a relatively few different types of system elements. Thus, high levels of both functional capability and modularity will be achievable with a correct approach to system architecture.

By configuring the system architecture to be fault-tolerant and reconfigurable, high levels of reliability, maintainability, and availability can be attained as well as modularity. A fault-tolerant system design, coupled with the modularization described above, can provide high levels of coverage of failures and the inherent capability to reconfigure the system after a failure to thereby maintain system capability. In addition, the high level of fault isolation capability inherent in the fault-tolerant architecture will allow isolation of the fault to a module. Thus, maintainability is enhanced because the failure is accurately diagnosed on-line to the level of a module, which can subsequently be replaced by a straightforward maintenance procedure. In addition, the fault-tolerant architecture can allow the system to function, possibly at degraded but acceptable levels of performance, for extended periods of time. As modules fail and repeated reconfigurations occur, the avionic system will degrade gracefully. However, the aircraft will be available to fly numerous missions, with acceptable levels of performance, before maintenance actions are necessary.

The system architecture envisioned here can also support the very high levels of functional integration that are emerging as requirements for future systems. As mission requirements increase, more and more of the functions that were formerly separate are becoming mutually dependent. Of particular significance is the increased dependence of the flight path control function upon other avionic system functions. Terrain following and integrated fire/flight control are two examples of this increasing trend. As the trend proceeds, more and more avionic functions will become flight critical and the resulting severe requirements imposed upon system integrity can only be supported by a modular, fault-tolerant, architecture.

In addition, integration of information within the avionic system can serve to enhance the fault-tolerance of the system. Failure diagnosis in sensors can often be improved by comparison of information from diverse sources. For example, radio navigation information can be used to diagnose inertial sensor failures. In effect, a highly favorable synergystic effect can be envisioned whereby modularization, fault-tolerance and integration are mutually supportive in achieving performance, reliability, maintainability, and availability.

4. PROCESSING

Processing is the primary generic function by which almost all applications functions within the avionic system are implemented. It also provides the underlying organization and management of the entire avionic system. As such, the core information processing system is crucial to the survival of the vehicle and crew, and must be as reliable and survivable as other critical functions within the aircraft, such as primary structure and flight control. This fact, plus the level of complexity required to support the total complement of avionic functions, requires that the core avionic system be a distributed, fault-tolerant, reconfigurable processing system.

The processing architecture of this system must support local, regional, and global functions. For example, a local function would involve the processing dedicated to a particular sensor, whereas a regional function could be the service of all crew displays, and a global function could be the overall management of avionic system resources. In addition, the system should be able to support selective levels of reliability of functions in an efficient manner with minimal complexity.

These requirements imply a distributed information processing system, implemented in the form of clusters of fault-tolerant processors, tied together by a set of data busses. The clusters may be general purpose, parallel processing, signal processing, or other types of machines.

Integral to this architecture is the concept of reconfiguration whereby the system automatically adapts to failures or damage to individual system elements. As failures occur, the fault-tolerant mechanisms embodied within the system automatically detect and identify failures. The system is then reconfigured so that the failed elements are replaced by on-line spares with no loss of performance. As more failures accumulate and spares are exhausted, the reconfiguration mechanism produces a gradual and graceful degradation process, whereby the most essential functions are preserved while the least important are eliminated. By employing redundancy and reconfiguration in a selective fashion, the system can thus support functions at various required levels of reliability without excess system complexity.

The reconfiguration mechanism can also be used to concentrate resources of the avionic system to support particular mission phases. For example, computation resources could be concentrated on a particular target recognition problem, possibly at the expense of automatic navigation, when the mission phase warrants such concentrated action. Thus a very high level of overall system effectiveness may be achievable at minimal cost and complexity.

5. DATA COMMUNICATIONS PATHS

To support the modular fault-tolerant, reconfigurable architecture of future avionics, several high speed data paths must be available for use in communicating between modules. It will not be necessary that every module be connected to every high speed data path. This basic system design philosophy will lead to what can be referred to as a "bus oriented" systems in which all data and control communication requirements are satisfied by a relatively small set of hard-coupled busses. Also, this philosophy supports the concepts of modularization and reconfiguration as presented in previous sections as crucial features of future systems. The following paragraphs present a discussion of the various ideas and concepts which are peculiarly associated with data communication paths.

Data rate requirements for module-to-module communications that seem to be evolving in avionic systems range no higher than 500 megabits per second in order to cover most applications (there are, of course, projections, particularly in the electronic warfare area, of much higher requirements which have yet to be quantified with any substantial justification). It is felt that advanced architectures can be supported with an array of, at most, four data rates: 1 megabits/s (mb/s), 10 mb/s, 100 mb/s, and 300-500 mb/s. For any intermediate or higher data rate than can be justified, one can assume that a special bus would be defined. However, these four data rates should each be supported by their own individual bus technology, in order to assure that the results will satisfy all anticipated requirements. The four data rates will accommodate most system level control and data type information currently perceived for avionic systems of the time frame under consideration.

Transfer medium refers to the material from which the data path is actually constructed in order to support the point-to-point communication but excludes any connected electronics and/or optics devices. The 1 mb/s channel is viewed as a wire bus and the higher speed busses are probably going to be constructed from an optical medium (i.e., fibre optics, light pipes, air channels, etc.). The dominating problems which have to be solved are associated with energy losses and, in the case of optical media, mechanical connectability. Current trends indicate acceptable media will be available for military use in the time frame under consideration.

Physical interfaces refer to the types of devices that will be physically connected between the path medium and the system, which function to transform the incoming data from the bus waveform to the system's internal bus waveform and vice-versa. Generally, these "transformers" are referred to as transceivers and become increasingly complex with increasing frequency of the signals being used. The main technology problems in the area of physical interfaces are, for the most part, in the high frequency regime, i.e., 10 mb/s and above. These problems, naturally, lead to requirements for high frequency electronic and/or electro-optic receivers and transmitters. Current trends indicate that significant research and development work must be successfully performed to assure that military use of high speed transceivers will be possible in the time frame under consideration.

For communication to take place, the system must embody a prescribed algorithm, or technique, for transferring messages between system components - these algorithms are usually referred to as "protocols." In order for a system design to be maximally transparent to technology changes, the system communication protocol must be defined and established as a standard. Currently a standard exists for the 1 mb/s communication channel but not for higher data rates. Therefore, there is a requirement for establishment of acceptable universally usable interface standards for internal aircraft communication. The criticality of such standards cannot be overemphasized if modular, reconfigurable, internationally usable avionic systems are seriously anticipated.

In summary, if future avionic systems are to support the concept of an integrated system (i.e., modularity, resource sharing, etc.) it seems clear that a well-defined bus structure will be needed. Such a structure will ensure technology transparency which, in turn, allows continuous insertion of new technology in an orderly and economic way. Attributes of systems with such a structure will include reliability, maintainability, and availability (RMA) and, as well, survivability. Current projections are that no more than four different frequency regimes are required for the time frame under consideration and that research and development is required in high frequency transceivers. Also, work in the area of communication protocol standards must be established and supported on an international basis.

6. SOFTWARE

An Avionic system is only as good as the information it receives, processes and communicates either to the automatic elements in the system or to human operators in the aircraft or on the ground. The processing capability depends upon the availability of processing hardware and, most importantly, upon the availablity of a proven suite of flight worthy software.

Although the Operational Flight Program (OFP) is the final output of the software development process, it should be remembered that beneath this application software there is a large amount of support software which is necessary if the design, development, testing, verification, and validation of the OFP is to be undertaken in a timely and cost effective manner. The need for standards in this field is just as great as in the hard ware area and the payoffs are of equal or greater value.

Any modern avionic system contains a large variety of embedded software ranging from complex signal processing programs to flight control programs, all of which require extremely high integrity. The complexity of this software is reaching the stage where its development can be a pacing item in the development of a new weapon system.

There is a great diversity in the software (memory, speed, integrity requirements) needed for the successful operation of a modern aircraft. Moreover, the requirements for high integrity in the flight control program are such that the verification and validation of the software becomes of paramount importance. To achieve the required low probability of loss of a military aircraft due to a failure of the Flight Control System (FCS) of 1×10^{-7} per hour of flight, it is necessary to employ fault tolerance techniques to ensure that the FCS systems shall remain operational after a fault in either the hardware or software. The trend toward increased integration of other functions with the outer loop control functions of the FCS (e.g., TF/TA) will increase the need to apply these failsafe techniques across a wider range of aircraft functions. This in turn will mean that there will be an increase in the software integrity required of these functions.

The processing requirements for sensor systems such as FLIR and Radar are such that parallel processing methods will be needed to provide the throughput required. While hardware for such processors is being developed, there is no equivalent software development. It is doubtful that the software methodologies being developed for current systems will be suitable for parallel processors; hence, new methods will be needed.

With this diversity of software requirements there is a real danger that there could be a mammouth increase in the support software needed to develop the various OFPs. Unless this is controlled, the support problems encountered on current in-service aircraft due to the multiplicity of languages used in these OFPs will be repeated in the next generation of OFPs due to the diversity of the support tools used. It is essential that software support tools are integrated into a total software support environment and this support environment be standardized to some level such that all avionic software development teams using the same higher order language use a common set of mature support software.

7. FAULT DETECTION/FAULT ISOLATION

Fundamental to the successful implementation of a modular-based system architecture is the ability to detect and isolate faults (fault detection and fault isolation (FD/FI)). FD/FI is essential for maintenance in order to initiate the removal and replacement of a failed module. FD/FI is also essential for dynamic reconfiguration. Prior to reconfiguration, it is obviously necessary to determine what part of the system has failed so that a replacement function can be brought on-line.

FD/FI for maintenance is driven by the repair philosophy. If 2-level maintenance is desired (no intermediate level), then it will be necessary to detect and isolate faults to the replaceable subassembly. In a module-based architecture, this requires that each module shall contain levels of self-test capability approaching 100 percent. This can be accomplished by techniques such as the utilization of dedicated test chips on each module, on-chip testing, and by interface wrap-around testing.

The level of FD/FI for reconfiguration will be a function of the system reconfiguration design. This, in turn, will be established by a trade-off of functional reliability, cost, volume, etc. For example, if reconfiguration is designed at a module level, then FD/FI to the module level will be required. If reconfiguration is at a cluster of modules, or at the Line Replaceable Unit (LRU) level, then FD/FI will only be required to that level. The key issue is that FD/FI needs to be an integral part of the system design at all levels and is especially important for designing the overall system architecture. Levels of FD/FI and methods of fault reporting are top down system design issues that need to be implemented in a consistent, uniform manner; not as an afterthought.

FD/FI for cables and connectors is essential. Data indicates that failures in cables and connectors represent a significant percentage of failures particularly in older airplanes. With higher data rates and lower expected excitation levels in future systems, the number of cable/connector induced system failures will likely increase. Consequently, it is essential that comprehensive FD/FI to cables and connectors be achieved.

8. AVIONIC SYSTEM FUNCTIONS

Avionic system integration technology is the enabling technology which allows the achievement of the high level of automation which we are driving toward. A way to describe the application of this technology is to define a set of avionic system functions, which, when taken together, yield what we commonly refer to as the automated cockpit. These functions are:

Vehicle management

Display management

Sensor management

Weapons management

Information management

Diagnostics management

Total aircraft automation is achieved by the integration of these functions into an efficient and orderly operating system. Additionally, many of these functions involve several avionic sub-functions which also need to be integrated into the overall operational system. A brief description of these functions is contained in the following paragraphs.

The vehicle management function assures the general integrity of the aircraft by integrating flight path control, stability systems, navigation, propulsion control, and power systems. An important part of this function is diagnostic management for the entire aircraft, including mission avionics. Subsystems which are integrated by this function include the autopilot, stability augmentation, propulsion control, and other integrated functions such as terrain-following.

The display management function integrates and manages all display systems, including display information for mission avionics such as sensors and weapon control. The function is concerned with display data processing and management, but not with the display equipment and presentation design, which is the domain of the display subsystem. Integration may include engine data, flight data and attitude display, fire control, radar, EW, system status, and numerical data.

The sensor management function integrates the various sensor subsystems to respond to the time-phased needs of the mission and the commands of the crew. The function controls the various modes and sequences of operations of each sensor, and frequently deals with sensor data which has been pre-processed to some degree. Subsystems integrated include sensor functions such as radar, EO and IR.

The weapons management function integrates stores data, weapons fuzing and initiation, and fire control. Typical subsystems in this function include the fire control subsystem, missiles, weapons release, chaff and decoy dispensers, smart weapon initialization and guidance, weapon ballistics for free fall weapons, and others.

The information management function integrates the other functions by providing sensor information to the fire control subsystem, for example, and vehicle information to the display subsystem. The emphasis is on information flow, rather than raw data. This function includes fusion of data from various sources from within the aircraft and from data from external sources. Automated decision advisories and automated action control are included in this function as appropriate.

The diagnostics management function oversees the overall health of the aircraft and provides diagnoses of failures within the damage to the aircraft. These diagnostic functions encompass both the vehicle and all its subsystems, including the avionics system itself which is providing the diagnostic function. Overall system resources are reconfigured once an anomoly is identified, to allow the overall vehicle system to continue to function effectively in spite of failures or damage.

It is clear that implementation of these functions requires intensive application of processors, data communication paths, software, and fault detection/fault isolation, i.e., avionic system integration technology.

9. SYSTEM DESIGN METHODOLOGY

The total development cycle of a weapon system is shown in Figure 1. As can be seen in the figure, the weapon system is initially specified at a high level and successfully partitioned into systems and subsystems, with the degree of detail increasing with each level of partitioning.

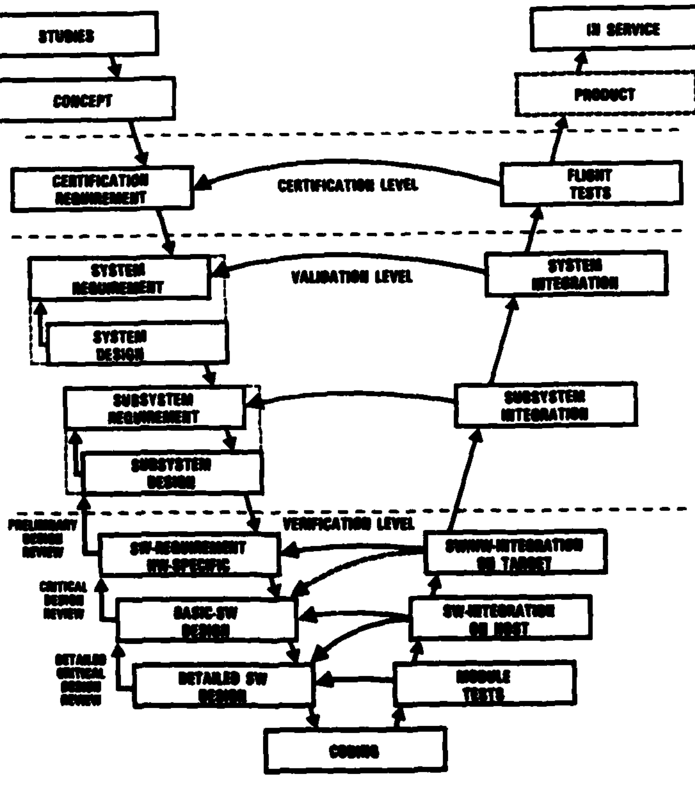

Figure 1. Total Development Cycle

If the complexity shown in Figure 1 is to be managed successfully, then a system methodology must be developed which allows the progression from concept, to requirements, through design, software development, integration and testing to occur in an orderly, controlled, and visible fashion. The system design category is particularly critical and may be further divided into three phases: functional design, physical design, and integrated design.

The functional design phase defines what the system is required to do without attempting to specify how this is to be done.

During the physical design phase, the system architecture is structured down to the various elements which are identified and specified.

The integrated design phase maps the functional design into the physical design and defines the data interface and control mechanisms.

As shown in Figure 1, verification, validation, and certification requirements (which also form part of the development cycle) must also be considered.

To enable the system design to proceed, it is necessary to establish a design environment within which the system design team can operate. This environment is similar in concept to the programming support environments typified by the ADA Project Support Environment (APSE) under development as part of the ADA language initiative.

While the APSE is concerned only with the software part of a project, the environment considered necessary - an Integrated Project Support Environment (IPSE) - should enable the complete system development environment to be supported. In addition to supporting design development, testing, and validation and verification (V&V), there are also additional functions which must be included in the IPSE to allow control to be exercised throughout the design phase. These functions are: (1) Project Management, (2) Estimation, (3) Documentation, and (4) Configuration Control.

Such an environment does not currently exist although work is proceeding in a number of areas to establish an IPSE. It is unlikely that the IPSE will be developed as a single project but rather it will likely be an evolutionary development over a period of time.

In providing guidance for the development of a good development environment, there are two key factors. These are: (1) A set of standards which will encourage tool developers to conform to them, and hence will promote the development of flexible and interchangeable tool sets; and (2) A set of measures so that good products can be easily and widely recognized. It is vitally important that both of these factors should be supported and able to be adapted to meet changing needs. An adaptable and changing set of standards may sound like a contradiction in terms, but this is not, in fact, the case. If a standard changes too quickly, it loses the confidence of its users and becomes valueless; but equally important, if it changes too slowly, it ceases to relate to the real world and becomes not a standard but a monument. Change in a set of measures is less unsettling, but to some extent the same criteria apply.

The advent of the IPSE will be brought closer by establishing an effective research and development effort to address a number of key areas. Among these are:

(a) <u>System Science</u>. This subject is at a level above that of software science and computer science. Essentially it is concerned with methods for developing large scale systems. While there is some academic interest in the subject, it is very much in its infancy.

(b) <u>Design Methodologies and Tools</u>. There exists a need to produce better design tools at a system level as well as at the hardware and software levels.

(c) <u>Failure Prediction Techniques</u>. Techniques are needed to predict the probability of failure of a system - both hardware and software during the design phase.

(d) <u>Control Techniques of Large Scale Processors</u>. While VLSI technology offers the promise of large parallel processors, there is little activity in the design and development tools needed to specify and produce software to operate on these processors.

(e) <u>Standards</u>. In order to foster the IPSE concept, a set of interface standards must be developed to enable the incremental development of the IPSE to take place.

10. IMPACT OF AVIONIC SYSTEM ATTRIBUTES ON OPERATION AND SUPPORT

The impact of the new aircraft system technology on the operational capabilities and the support requirements in the NATO arena will now be briefly discussed. Although avionic system architecture and design does not contribute directly to specific flight performance improvement, it provides the infrastructure which enables the accommodation of elements which do provide such performance improvement. Its impact on the total force structure and overall mission efffectiveness falls mainly in three areas: availability and sustainability, mission effectiveness, and cost effectiveness. Each of these is addressed specifically in the following paragraphs.

11. AVAILABILITY AND SUSTAINABILITY

To the operational forces, the availability and sustainability should be the earliest apparent advantages of the system integration technology discipline. It is estimated that availability of the total avionic system could improve by approximately 20 percent for modest complex systems. In very complex avionic systems, the availability improvement might be as much as 50 percent. These estimates are, of course, dependent not only on the total avionic system complexity, but also on the specific system architecture chosen and the degree and depth of standardization applied. It should be noted, however, that the availability improvements arising from the proposed system integration are in addition to those obtained from increased reliability or ease of maintainability ascribed to individual avionics elements.

A large part of the improvement in availability derives from the capability for dynamic reconfiguration of the avionic system in flight in response to one or more failures in the system. The appropriate memory unit, for example, can reassign its function to another memory unit. This will enable critical functions to be continued while less critical functions are attended to less frequently or less accurately. The capability to reconfigure the avionics system automatically in case of failures also contributes to sustainability in spite of battle damage, since some missions can still be successfully completed even though they would otherwise have been aborted due to battle damage to a single avionics element. This applies to flight critical functions as well as to those critical to mission success.

Systems fault tolerance permits deferred maintenance and adds to system availability. Hence a system will continue to be flight worthy and mission capable after some failures, so the operational commander can shift the maintenance tc a less critical time. This places the period of availability more under the management control of the commander, improving the effective availability and allowing higher peak sortie rates. In addition, improved avionic system availability will permit higher average sortie rates.

12. MISSION EFFECTIVENESS

The system integration discipline provides improvement in overall mission effectiveness in several ways. One of these is the improved availability and sustainability highlighted in the previous paragraphs, permitting, in particular, higher sortie rates.

One of the most important contributions to mission effectiveness is that the design architecture described will enable fusion of sensor data from within and without the aircraft. Although the integration discipline alone will not accomplish fusion, it will provide the infrastructure without which such fusion is probably not practical. The advantages offered by fusion include improvements to survivability, penetration of enemy defenses, and interoperability. The degree of improvement in these factors depends on the sensor data, how it is fused, and the operational scenario. But the system integration architecture is the enabler.

Mission effectiveness is also improved by presenting the opportunity for reconfiguration of the aircraft for a different mission. The integration architecture will permit the addition of special mission payloads, either weapons or sensors, and permit relatively simple avionic system configuration without additonal hardware changes to other avionics equipment.

This same attribute will permit evolutionary changes in mission capability throughout the life of the airframe. The integrated design should allow major avionics changes to be made in the field, thus further improving the real availability of the aircraft.

13. COST EFFECTIVENESS

The most important impact of the system integration architecture of the 1990s is in reduced life cycle cost of the avionic systems. Although some potential exists for savings in initial procurement costs, the real savings occur after deployment.

An architecture with standard interfaces will reduce the complexity of ground support equipment, particularly that at the operational maintenance level. The increased automatic fault isolation built into the system for the purpose of dynamic reconfiguration will provide fault data from the actual time of occurrence of the failure, as well as an estimate of which device is at fault. This will reduce maintenance time at the operational level. The standards imposed by the integration design architecture will reduce the number of spares required at all levels.

Perhaps the most important life cycle savings will arise from the capability of the system to accommodate advances in technology. Because of the interface discipline, the system design will be essentially transparent to those technology improvements which leave the function unchanged. Thus, improved sensors can be inserted with less down time, not only reducing upgrade costs, but also improving aircraft availability.

11. AVIONIC SYSTEM IMPACT ON THE CONDUCT OF AIR WARFARE

Technology's impact upon the avionic system and upon the aircraft's operational capabilities has been described in the previous paragraphs. In order to assess the impact of technology upon the conduct of air warfare, it is necessary to take into account not only the benefits which technology affords to the core system itself, but also those to the sensors and other subsystems comprising the total system.

The primary impact of the new technology is to increase the effectiveness of the total weapon system in carrying out its mission and in defending itself. For example, the aircraft will be exposed less to danger while enroute to its target, through the benefit of flight-path control allowing greater use to be made of terrain-screening and other hiding mechanisms (e.g., cooperative emission control and jamming). It will be able to make single-pass attacks through the use of more capable sensors, data fusion, cooperative operation, pilot-aided weapon aiming and release, and smart weapons.

For surveillance missions, the increased capability of the sensors will provide greater effectiveness and will reduce the time taken from acquiring the raw intelligence information to tasking the tactical response/initiative. Thus the battle will be faster-flowing and dynamic; this in turn leading to greater confusion and total dependence upon the effectiveness of the complete chain from intelligence-gathering through decision-making to tasking. However, any unnecessary delays in this chain will reduce effectiveness, thus laying great stress on the successful implementation of C^3I technologies.

The new technology, coupled with the system's architecture and design philosophies and methodologies, will yield more flexible weapon systems. In the first instance, this will result in greater system's availability through the incorporation of fault-tolerance and graceful degradation. Thus, the military commander will have a fighting force available to him for longer; his actions are more sustainabile in terms of higher sortie rates, and longer times before the system is totally unusable. Secondly, he is able to task his aircraft more flexibly, changing his sensor and weapon fits more readily, the software reloads being rapidly incorporated as a result of the modularity of the architecture.

The greater sustainability of the systems, the incorporation of internal self-test and the greatly reduced dependence upon ground support facilities for turnaround, coupled with appropriate vehicle design criteria, will permit a much greater flexibility in the use of remote bases for operation. This will increase the tactical responsiveness of the fighting force. In addition, the logistic supply problems for remote bases will be reduced toward the ideal of ordnance and fuel only.

12. SYSTEM TECHNOLOGY NEEDS

Much of the progress in avionic systems that is anticipated depends upon current and anticipated progress in a number of diverse technologies. Research and development in some areas is well established, but for other critical technologies progress is less certain. It is imperative that effort and resources be applied to those areas in future years. The following paragraphs briefly describe some of these system technology needs.

(a) System Design Methodology. There is an insufficient technology base in the area of large scale system design and development for critical applications. Progress is necessary in developing methods and tools for designing and verifying highly integrated, fault-tolerant, avionic systems.

(b) High Data Rate Technology. High speed data rate communication technologies are needed for critical applications in which system integrity is a primary requirement.

(c) System Management Function. The complexity of future avionics systems will require a new technology base in the area of automation of system resource management. Functions of data bus management, data base management, system diagnostics and reconfiguration, must all be largely automated in future avionic systems. Here too, emphasis must be placed upon the integrity of these functions because of their criticality to overall system operation.

(d) Standards. Much of the success of these future systems depends upon standardization of both hardware (probably form, fit, function) and software. Current efforts to standardize must be accelerated.

(e) Software. Software costs are accelerating out of control. More effective methods of automating software development and tools for validation and verification of software are critically in need of development.

(f) Parallel Processing. There is an emerging need for orders of magnitude increases in computation throughput in future avionic systems. Parallel processors appear to be the most promising solution to this problem. There is much effort currently under way in terms of hardware architectures for parallel machines. Reliability and integrity of these architectures for critical avionics must be addressed as well as the entire issue of flight software for these machines. Artificial intelligence techniques should be examined as a basis of this effort.

13. CONCLUSIONS

The next generation avionic systems should be designed for fault tolerance and deferrable two-level maintenance with a maximum use of common, functional modules (hardware and software). NATO Interface Standards (signal input/output, physical and power) need to be developed as the basis for common modules and for reconfiguration. Particular emphasis is needed in the architectural design area. Interface standards should result in improved availability, effectiveness, competitiveness and reduced life cycle costs.

To capitalize on the significant investment that the NATO nations are making in the development of Avionic system software, adherence to NATO adopted standards will be vital.

14. ACKNOWLEDGEMENT

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IMPROVED COMBAT PERFORMANCE USING RELAXED STATIC STABILITY AND A SPIN PREVENTION SYSTEM (FBW JAGUAR)

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SUMMARY

This paper describes the theoretical performance benefits that can be obtained by designing an aircraft that is naturally unstable in pitch and artificially stabilised by use of active control technology including an integral stall departure and spin prevention/'g' limiting function. It goes on to describe how many of these benefits have been successfully demonstrated during flight trials on the FBW Jaguar demonstrator aircraft.

The flight trials are briefly discussed including the results of the stall departure and spin prevention system assessment with examples of severe dynamic combat manoeuvres made possible by such a system. The combination of leading edge wing strakes and longitudinal instability gave improvements in aircraft turn rate, acceleration, and field performance, thus providing a practical demonstration of many of the theoretical benefits described earlier.

The FBW Jaguar flight control system was designed from the outset as a production system with the aim of identifying production clearance procedures so this experience leads straight into new combat aircraft such as the EFA.

PART A: DESIGN STUDIES

1. INTRODUCTION

In combat situations, manoeuvrability and agility are of prime importance in bringing even sophisticated and capable weapons to bear. Three key parameters to success can be identified as

- Maximum sustained (thrust-limited) turn rate (STR)
- Maximum attained (lift limited) turn rate (ATR)
- Specific excess power (SEP)

The last is a measure of the ability to regain energy by climbing or accelerating, and the extent to which a pilot can afford to exceed the STR boundary during combat depends on his ability to regain energy using maximum SEP.

Sustained manoeuvrability is the product of both lift/drag ratio and thrust/weight ratio. Efficient subsonic cruise and loiter demand high values of lift/drag ratio over as wide a range of lift as possible. Similarly, high attained manoeuvrability demands low wing loading and efficient high lift devices. The most efficient wing for combat performance is therefore one that provides maximum lift with the lowest drag in manoeuvring flight, over as large a range of lift as possible. In recent years, advances in wing design methods using powerful computers have enabled designers to achieve the required pressure distribution to minimise drag at the design value of lift. However, a high lift wing section is highly cambered, and is unsuitable for transonic dash and supersonic acceleration.

This has resulted in the widespead use of variable camber wings for high speed manoeuvring, and these wings are designed with leading and trailing edge flap deflections scheduled with incidence and airspeed to provide near optimum performance over a large part of the design flight envelope.

2. IMPROVED COMBAT PERFORMANCE DESIGN

2.1 Combat Wing Design

A typical family of lift/drag curves for a modern combat wing is shown on figure 1, which shows that the minimum drag envelope can be achieved by suitable scheduling of leading and trailing edges. The benefits produced with an optimum schedule are shown in figure 2. However, use of trailing edge devices to increase camber generates increased rear loading on the wing as incidence is increased. On a conventional tailed aircraft this leads to increasing down loads on the tail to trim, assuming the c.g. is positioned for natural aircraft stability. These tail loads are additive to the trimming loads required for an aircraft with positive natural stability and are detrimental to total aircraft performance, and so lead to significant trimmed drag and lift penalties, thus detracting from the benefits of the variable camber wing design. If the aircraft were to possess negative natural stability, these two components would tend to cancel out; i.e. the trailing edge flap deflection itself would be used to trim the aircraft thus minimising tail loads.

2.2 Relaxed Static Stability

From the above discussion it is clear that the benefits of variable camber wings can only be fully exploited if associated with artificial stability in pitch, since the balancing load on the tail will then be small, or if the aircraft is unstable tail off, the tail load will be up and beneficial to total aircraft lift (figure 3).

Studies at BAe Warton have shown that for a conventional tailed aircraft such as Jaguar an improvement of 12% in trimmed lift can be obtained with an aft located c.g., both with flaps up and down. This additional lift can be used to improve aircraft performance, or alternatively the aircraft size can be reduced to maintain performance as illustrated in figure 4. By taking advantage of the reduced drag, which in turn leads to reduced fuel requirements and reduced engine size a reduction of more than 12% in wing area is in fact possible. Results of a BAe Warton study based on a Jaguar aircraft are shown on figure 5 which shows the possible reduction in aircraft size obtained by use of artificial stability while maintaining aircraft performance.

2.3 Canard Configurations

Modern combat aircraft with high supersonic performance requirements are designed with low aspect ratio wings, and when coupled with artificial stability in pitch, these configurations lead naturally to the use of canard configurations. A canard configuration with natural stability in pitch involves high loads on the foreplane, leading to high drag in manoeuvring flight. However, use of artificial stability in pitch leads to a more lightly loaded foreplane. At supersonic speeds, the aerodynamic centre moves aft, requiring an uploaded foreplane to trim, thus providing a more efficient solution than a downloaded tail. Another benefit of using this type of configuration is that it has cleaner afterbody lines and a shorter afterbody, due to the absence of tailplane and spigot supporting structure, and this leads to lower supersonic drag.

2.4 Fly by Wire (Active Control Technology)

We have seen that the benefits of variable camber wings can be fully exploited only if used in conjunction with artificial stability in pitch. This leads to FBW control systems which allow use of ACT concepts.

Many combat aircraft cannot use the full lifting capability of the wings since they are limited by lateral/directional misbehaviour long before the wing stalls. The pilot must therefore allow an incidence or 'g' margin in order to avoid such phenomena. By including stall departure and spin prevention (SDSP) in the FCS design, the aircraft can safely penetrate the stall region and so exploit its full lift capability and in addition, provide a carefree manoeuvring capability to the pilot. Figure 6 illustrates a typical case where use of SDSP results in an improved incidence and 'g' capability.

The SDSP system is designed to augment stability and restrain the use of excessive departure inducing control as limiting conditions are approached. The incidence limiting function is scheduled with dynamic pressure to prevent departures and coupled with normal g limiting, the FCS has the capability to provide the pilot with a carefree manoeuvring capability throughout the flight envelope.

When these concepts are coupled with the benefits described earlier of artificial stability, the designer is fully exploiting the capabilities of the airframe (Figure 7).

PART B FLIGHT TEST EXPERIENCE ON THE FBW JAGUAR

3. THE DEMONSTRATOR PROGRAMME

The FBW Jaguar programme represented a research programme whose overall aim was the design development and flight demonstration of a safe practical full time fly-by-wire flight control system for a combat aircraft. The prime objective was the identification of the design methodology and airworthiness criteria necessary for flight certification of such a system, which was designed as a production system, and it was not intended to demonstrate the full aerodynamic benefits of ACT. However, the flight programme included both a demonstration of the effectiveness of the integral stall departure and spin prevention system (SDSP) and a detailed assessment of the aircraft behaviour in a series of aerodynamically unstable configurations and the results of these trials provided a practical demonstration of many of these benefits.

3.1 Demonstrator Aircraft

The FBW Jaguar demonstrator is a modified single seat Sepecat Jaguar which started life as a standard production aircraft and served with the RAF for several years before being returned to British Aerospace Warton for modification as a demonstrator aircraft. Initially, only minor changes to the airframe were made in order to accommodate the quadruplex digital flight control system and an extensive instrumentation system. All the mechanical control rods, autostabilisers and original powered flying control actuators were removed leaving the aircraft totally reliant on the digital FCS. Provision was made for non jettisionable internal ballast to be carried and a spin recovery parachute system could be fitted in place of the standard brake parachute.

At this stage of the programme, the aircaft was externally little different from a standard Jaguar but the internal ballast together with alterations to the fuel system management and carriage of underwing fuel tanks allowed manoeuvre margins of +15% to -4% AMC to be progressively assessed.

In order to increase the level of aerodynamic instability, large wing leading edge strakes were then fitted to the aircraft. The effect of these strakes was to move the centre of lift forward by about 11% AMC which in conjunction with ballast and underwing fuel tanks enabled flight assessment of manoeuvre margins in excess of -10% AMC to be carried out. This configuration provided a practical demonstration of many of the benefits which could be achieved with an aerodynamically unstable aircraft. Figure 8 illustrates the aircraft in its straked configuration and a more detailed description of the aircraft and its systems can be found in Reference 1.

3.2 Flight Control System

The flight control system (FCS) is basically a quadruplex digital system with no manual reversion. Quadruplex position sensors are used to sense pilot control demands in terms of stick, pedal and trim inputs, and quadruplex rate gyros sense aircraft pitch, roll and yaw rates. Four identical digital flight control computers (FCC) are used to process these signals together with a variety of other sensors. The resulting command signals are used to control the two taileron, two spoiler and one rudder actuators. In order to convert the quadruplex signals from the FCCs into the sextuplex signals required by the duo-triplex actuators, the four FCCs are supplemented by two actuator drive and monitor computers. In addition to the quadruplex primary input sensors, sensors of lower redundancy are used for those functions which may be necessary for optimum handling qualities but which are not necessary for safe flight. These are dynamic pressure, static pressure, incidence and sideslip which are all triplex secondary sensors; and flap position and airbrake position which are duplex sensors. Triplex dynamic and static pressures are provided by three pitot static probes (the standard nose boom and two side mounted probes). Triplex incidence and sideslip signals are provided by four airstream direction detector probes (ADD) mounted around the nose of the aircraft. A complete description of the FCS can be found in References 2 and 3.

3.3 Control Laws

The control laws implemented within the digital FCS were designed to give the aircraft good handling qualities over the full flight envelope and the SDSP function was an integral part of these control laws.

In the pitch axis, pitch rate demand from the stick is compared with pitch rate and incidence to produce an error signal which is fed to a PID controller. The stick path also includes a non linear "manoeuvre boost" path to give rapid initial response to large stick inputs. Pitch control at all conditions is provided by symmetric deflection of the all moving tailerons. The SDSP function limits incidence to the design value by reducing stick command gain as incidence increases and utilising incidence feedback.

The lateral control system is a rate demand system where maximum demand rate is a function of flight condition, incidence and configuration.

Roll control at low incidence is essentially provided by the spoilers. As incidence is increased, differential taileron is used to augment the spoilers. A spoiler to rudder interconnect is provided to improve turn co-ordination and tracking, and to prevent autorotation at low 'g'. The SDSP function is achieved by limiting the effective roll stick authority at high incidence.

The yaw channel comprises a wind axis d.c. blocked yaw damper with directional stiffness augmentation by sideslip feedback. Wind axis yaw rate is synthesised from aircraft roll and yaw rates using a roll to yaw crossfeed. A second roll rate crossfeed term is used to improve turn co-ordination at low speed. These terms are summed with rudder pedal and yaw trim commands to produce the rudder demand.

Rudder pedal authority is scheduled with airspeed and incidence, the latter providing the SDSP function.

3.4 Flight Test Programme

The overall flight trials programme which was performed in total at BAe Warton was divided into 5 phases as described in References 1 and 4.

Phases 1 and 2 comprised a general aircraft and systems shakedown leading on to an initial handling assessment and a flutter test flight envelope expansion programme.

Phase 3 provided a detailed handling assessment in a number of longitudinally stable aircraft configurations and included the demonstration of the effectiveness of the SDSP function.

Phase 4 comprised an assessment of the longitudinally unstable aircraft at stability levels down to -4.5% AMC.

Phase 5 was an assessment of the straked aircraft over the stability range of +3% to -10% AMC.

The benefits of the SDSP function were demonstrated in full in Phase 3 and in part in Phases 4 and 5.

The performance benefits of the FBW aircraft were demonstrated in Phase 5 by comparing these results with results obtained in Phases 3 and 4.

3.5 Performance Benefits

During the last phase of the flight programme, manoeuvres flown as a part of the handling assessment were used to gather performance data. In order to do this, the test technique was modified so that the manoeuvre could be used for performance analysis without compromising the prime objective of the test point. For example constant throttle setting was used throughout the manoeuvre in order to obtain drag factors in the absence of calibrated engines. The results obtained were then compared with data extracted from similar manoeuvres performed in earlier phases of the flight trials.

The results of the analysis indicated that the ability to fly the longitudinally unstable aircraft produced clear improvements in both increased lift and reduced drag.

3.5.1 Lift

In the standard Jaguar configuration, i.e. before the strake was fitted, the effect of moving the centre of gravity aft is illustrated in Figure 9 where lift coeficients for two stability levels are presented. Compared with the stable configuration (a manoeuvre margin of +5% AMC), the unstable configuration (-1% manoeuvre margin) produced a lift increase of the order of 10% at moderate C_L.

In the straked configuration, the addition of the strake produced the expected increase in lift and this in itself could not have been realised without the ability to control this aerodynamically unstable configuration. Figure 10 illustrates the effect of further increases in levels of instability on measured lift coefficients and it can be seen that the highly unstable configuration (-9% manoeuvre margin) produced lift improvements of the order of 7% at moderate C_L compared with the moderately unstable configuration (-2% manoeuvre margin). Figure 10 also illustrates the combined effect of strake and large levels of instability. Compared with the standard Jaguar at +5% manoeuvre margin the straked FBW Jaguar at -9% manoeuvre margin provided dramatic increases in lift (nearly 30% at moderate C_L).

A similar picture emerged in the take off and landing configurations as illustrated in Figure 11. For the straked aircraft, the highly unstable configuration (-10% AMC manoeuvre margin) provided an increase in C_L of 7% at the take off incidence and 9% at the approach incidence compared with the moderately unstable configuration (-2% manoeuvre margin). When compared with the standard Jaguar the combination of strake and large levels of instability on the FBW Jaguar produced corresponding increases in C_L of 25% and 22% respectively.

3.5.2 Drag

The combination of strakes and large levels of longitudinal instability produced the reductions in drag illustrated in Figure 12. This presents typical plots of drag coefficient CD against $C_L{}^2$ for the unstable straked FBW Jaguar and a stable standard Jaguar. Because of the lack of calibrated engines and specialised instrumentation parameters, it was not possible to quantify the individual effects. However, the ability of the FBW Jaguar FCS to control the highly unstable straked aircraft produced considerable drag reductions and these were most obvious at high incidence. It was also noted by the pilots, that the unstable straked FBW Jaguar exhibited significantly improved rates of acceleration at transonic and supersonic speeds compared with the standard Jaguar.

In the take off and landing configurations, the combination of strakes and longitudinal instability again produced significant drag improvements with a 25%

reduction in drag at take off incidence and a 10% drag reduction at approach incidence being identified.

3.5.3 Combat Benefits

In the combat situation, the combination of lift and drag benefits identified above would increase both attainable turn rate and reduce the energy loss at high incidence. As an example, at a typical flight condition of 0.7 Mach 10,000ft. the highly unstable (-10% manoeuvre margin) straked FBW Jaguar would have a 3.5°/sec turn rate advantage and, at a high incidence, a speed loss which would be 1.7kts per second less than a standard Jaguar at +3% manoeuvre margin.

Although not directly related to air to air combat, the reduction in take off and landing speeds identified for the unstable FBW Jaguar would produce corresponding reductions in runway requirements. Thus in terms of operation from dispersed airfields, combat effectiveness would be increased by the reduction in runway requirements. For example, the benefits identified above would produce effective reductions of 22% in take off ground roll and 16% in landing ground roll on the highly unstable FBW Jaguar compared with the standard Jaguar, with corresponding improvements in engine out performance characteristics.

3.6 SDSP System Assessment

The full flight trials assessment of the SDSP function of the control laws was performed in a stable configuration with the aircraft fully prepared for such a potentially hazardous high incidence trial. The behaviour of the aircraft at high incidence proved to be so good that the trial progressed very rapidly to the combat assessment stage. Some 43 manoeuvre sequences were performed at full back stick and despite very aggressive manoeuvring, there were no signs of incipient departure and the aircraft was under complete control at all times.

The actual flight assessment comprised a series of test manoeuvres which provided a progressively more severe test of the SDSP system. As two pilots were involved, the majority of the test points were repeated in order to obtain as large a variation on pilot technique as was feasible within such a limited programme.

The trial commenced with slowdowns, wind up turns and straight pulls to full back stick with small lateral control inputs. These were then extended by applying full roll stick and full rudder inputs at 16° incidence and at full back stick in both trimmed and mis-trimmed conditions. Snatch pulls to full back stick were also flown, working up to very high rates of stick application (full back stick was achieved in 0.2 secs in the fast snatch pulls). The assessment progressed to more severe control inputs, including half roll stick rolling breaks to full back stick, 'diagonal' breaks to full back stick, full roll stick breaks to full back stick, and was concluded with two 'combat assessments' where a series of manoeuvres were strung together. Both project pilots were very satisfied with the aircraft behaviour throughout the trial, and the SDSP system generated a very high level of pilot confidence.

The incidence limiting function was unobtrusive to the pilot but highly effective in limiting the incidence to the design value as shown in Figure 13. It can be seen that even the most severe inputs did not result in more than a 3° overshoot of this value, and the FCS quickly brought incidence back to the limit. The pitch rates which could be generated were very impressive (up to 36 deg/sec) and always under control.

The control induced departure prevention function of the SDSP was also very effective in reducing roll and yaw control authority available to the pilot to a safe level at high incidence. However, even at full back stick, control authority was still sufficient to provide a highly manoeuvrable aircraft with good roll rates being achieved throughout the incidence range. This is illustrated in Figure 14 where peak roll rate as a function of incidence is presented and compared with that achieved on a standard Jaguar.

The combination of these two functions enabled severe dynamic manoeuvres to be performed. A typical example is shown in Figure 15 which illustrates a full stick rolling break. That is, with full roll stick applied at 1g, the stick was pulled to the aft stop as hard as possible and a full 360 roll performed. As can be seen, complete control was maintained at all times.

The final test of the SDSP system was a simulated combat assessment. Each pilot flew a series of aggressive manoeuvres linked together to simulate combat conditions. One of these sequences is illustrated in Figure 16 and was made up of the following manoeuvres.

- Rapid roll into full aft stop rolling break
- 360° roll on aft stop
- Centralised controls and unload to 1g
- Snatch pull to aft stop
- Full rudder/roll stick/back stick roll right through 360° roll
- Unload to 1g wings level and snatch pull to the aft stop and full rudder/roll stick/back stick roll left through 360°

- Unload to 1g and snatch pull to the aft stop, full right stick and rudder then reverse to full left stick and rudder all on aft stop.

Throughout this series of manoeuvres, which was flown totally without any constraint being applied to the rate or magnitude of control inputs, the SDSP functioned impeccably.

With the successful completion of these manoeuvres, it was hard for the pilots to envisage anything more that a practical pilot would want to do, other than to allow the airspeed to fall below 90kts (a limitation imposed by the use of standard airstream direction detector probes to measure incidence) that the FBW Jaguar could not cope with. The aircraft was easy and straightforward to fly at extremes of the flight envelope, and was not in any way disturbed by hard manoeuvring. As one of the project pilots commented "Even a relatively inexperienced pilot would be able to extract the maximum performance from this aeroplane".

Although the SDSP function was not specifically assessed during the subsequent flight trials phases, the presence of the SDSP system significantly improved both the handling qualities of the aircraft and flight safety. For example, when flying in the first unstable configuration, the presence of the SDSP functions within the control laws gave the aircraft excellent handling qualities right up to the incidence limit which was coincident with the SDSP incidence limit. Thus the pilots had great confidence manoeuvring at limiting conditions since rig testing had shown the continuing effectiveness of the SDSP in preventing loss of control on what was now an aerodynamically unstable aircraft. A further by product of the control induced departure prevention function of the SDSP was the excellent handling of the aircraft at the incidence limit with underwing stores fitted. (This was true for the strakes off and strakes on configurations). Handling qualities on the FBW Jaguar were far superior to the standard Jaguar and this enabled the FBW Jaguar to manoeuvre at significantly higher incidences. In fact the FBW Jaguar had the same incidence limit with or without stores.

3.7 Combat Benefits

In the combat situation, an SDSP equipped aircraft enables the pilot to manoeuvre the aircraft with minimal limitations and maximum confidence throughout the incidence capability of the aircraft. This was graphically demonstrated on the FBW Jaguar SDSP trial where the pilot had no incidence limit and so was able to fly "head out" at all times - a prime requirement for close combat. Full control inputs can be applied in any combination up to the maximum incidence achievable giving the pilot the ability either to take violent evasive action or to manoeuvre hard to obtain a tracking solution on a target with no risk of loss of control. Again this was demonstrated on the FBW Jaguar where violent coupled manoeuvres were performed with no build up of excessive sideslip and the aircraft under complete control at all times.

4. FUTURE AIRCRAFT

Flight experience gained on the FBW Jaguar has demonstrated the improved combat performance available on an aircraft equipped with an integrated flight control system which can provide excellent handling qualities in aerodynamically unstable configurations and an essentially carefree manoeuvre capability throughout the flight envelope.

Combat performance can be further improved on future aircraft such as the EFA by exploiting in full the benefits of combat wing design and natural instability in the design stage and using the integrated flight control system to stabilise the aircraft, provide control of the optimised wing high lift devices and to give the pilot a "carefree manoeuvre" capability.

REFERENCES

1. T. D. Smith, C. J. Yeo, R. E. W. Marshall, 'Ground and Flight Testing on the Fly by wire Jaguar Equipped with a Full Time Quadruplex Digital Integrated Flight Control System'. AGARD 35th Guidance and Control Panel Symposium Portugal 1982 'Advances in Guidance and Control Systems'.

2. R. E. W. Marshall, K. S. Snelling, J. M. Corney,"The Jaguar Fly by Wire Demonstrator Integrated Flight Control System" 1981 proceedings of Advanced Flight Control Symposium USAF Academy.

3. K. S. Snelling "Certification Experience of the Jaguar Fly by Wire Demonstrator Aircraft Integrated Flight Control System" AGARD Flight Mechanics Panel Athens 1983.

4. E. Daley An Update on Experience on the Fly by Wire Jaguar equipped with a Full Time Digital Flight Control System. AGARD 65th Flight Mechanics Panel Symposium Toronto 1984.

ACKNOWLEDGEMENT

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FIGURE 1 Effect of Combat High Lift Devices on Lift/Drag Ratio at Subsonic Speed

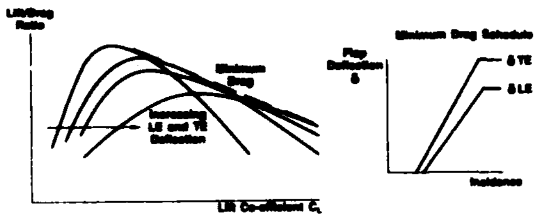


FIGURE 2 Improvement in Lift/Drag Ratio Using Variable Camber Wings

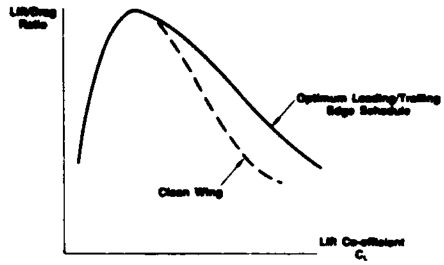


FIGURE 3 Benefits of Variable Camber with Artificial Stability

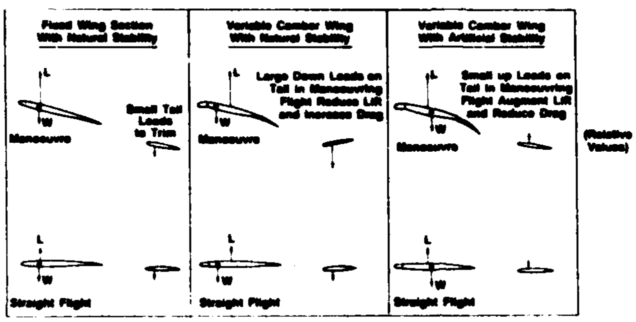


FIGURE 4 Effect of CG Position on Maximum Lift

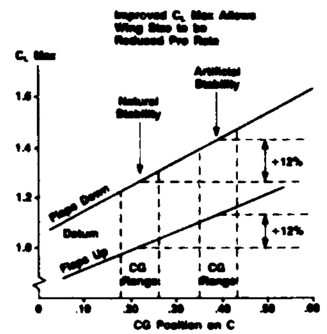


FIGURE 5 Effect of Artificial Stability on Aircraft Size

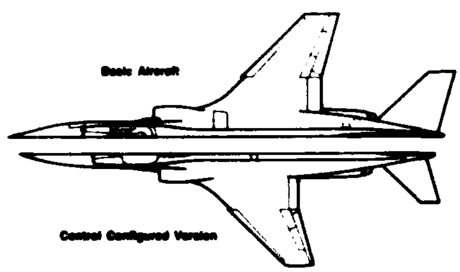


FIGURE 6 Improved Incidence Capability Using an SDSP System

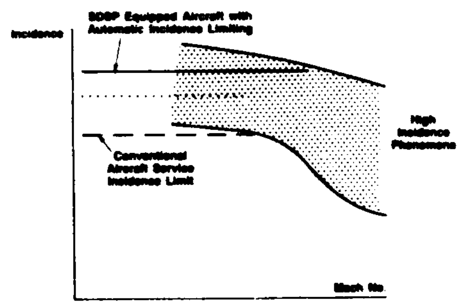


FIGURE 7 Major Benefits of FBW Technology

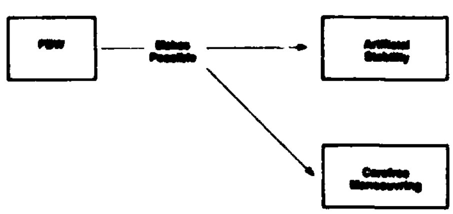


FIGURE 8 FBW JAGUAR WITH LEADING EDGE STRAKES

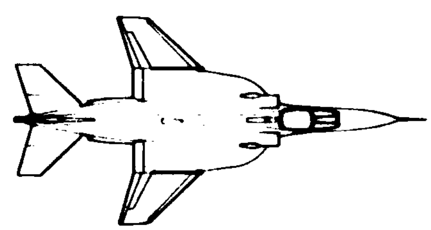


FIGURE 9 **Lift Improvements Due to Relaxed Longitudinal Stability**

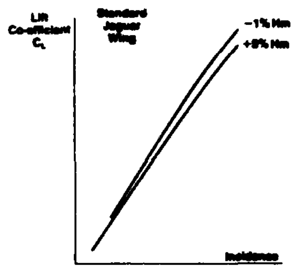


FIGURE 10 **Lift Improvements at High Levels of Longitudinal Instability**

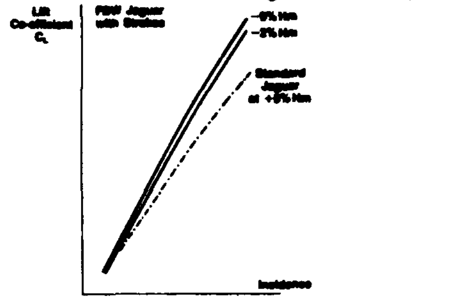


FIGURE 11 **Lift Improvements Due to Longitudinal Instability**

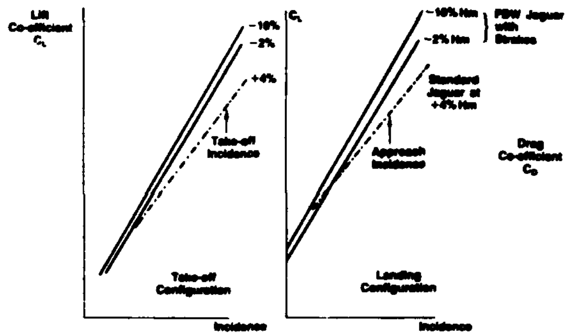


FIGURE 12 **Drag Reduction Due to Strake and Longitudinal Instability**

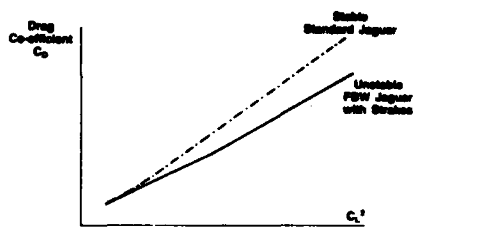


FIGURE 13 **Performance of Incidence Limiting Function**

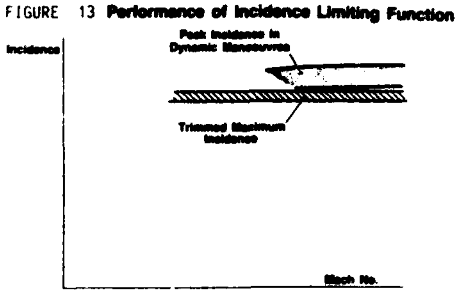


FIGURE 14 **Effect of SDSP on Roll Performance**

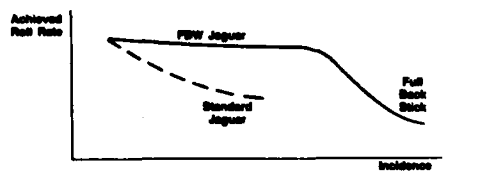


FIGURE 15 FULL ROLL STICK BREAK TO FULL BACK STICK

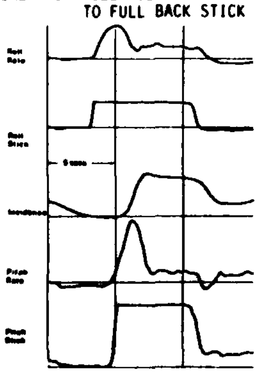
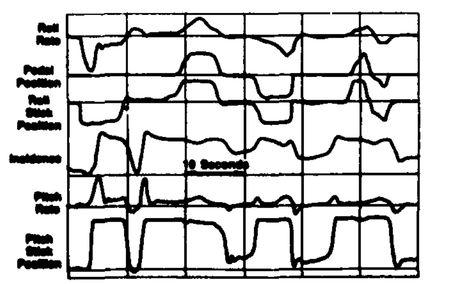


FIGURE 16 **Simulated Combat Manoeuvring**



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The Assessment and Evaluation of Combat Performance Improvements

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1. Introduction

Aircraft performance improvements, for combat or any other operational role, are becoming increasingly difficult to achieve. The dramatic year-by-year advances of the forties and fifties are long gone. Aerodynamicists have a much better understanding of the physical properties of the atmosphere and the shapes which can best be propelled through it. The relationships between the energy in fuel, and the conversion process into thrust are well developed. Structural engineers understand the mechanical properties of materials needed to build engines and airframes. All these factors have been exploited, and further improvements do not come cheaply. Only in the area of avionics can it be said that large benefits in the weight/cost/performance trade-off can be expected.

Nevertheless, the call for improvements in combat performance is as strong as ever. Designers continue to find a few per cent here and a few per cent there. There was little doubt in the fifties that doubling the range, or adding 50 knots to the top speed of a projected aircraft was beneficial, in terms of operational performance. Now, a small improvement in maximum lift, or a small reduction in supersonic drag, may be insignificant in one operational scenario, and may be the key to success in another.

2. Modelling in the Design Process

In the broadest sense of the word, models have always been used in aircraft design. Mock-ups, test specimens, rigs and wind tunnels all have a history which goes back to the beginnings of flight. The prediction of performance, stability and control, by solving mathematical equations has an even longer history.

The impact of computers on the design process parallels the impact of computers on life in general; in design, computers have, amongst other benefits, brought the widespread use of mathematical models.

First came freedom to solve complex equations by either analog or digital computers. Gradually digital computers took over, offering ever-increasing speed and capacity. Then came the terminals and graphics needed for CAD/CAM. Along with these developments, real-time computing has advanced the contribution of pilot-in-the-loop simulation, as distinct from mathematical modelling.

Now, computers are linked into massive networks, and the use of 'intelligence' is opening up even more possibilities to change the methods of design. The integration of these new methods has become a critical factor - how best to pull together the specialisations, and retrieve the benefits of the small-team approach of former years.
One important application of mathematical models which has emerged in this evolution has been their use in Operational Analysis. Operational Analysis is now an essential tool to assess both the design improvements which can be found in the traditional disciplines, and the more sweeping changes in operational deployment which follow from avionic fit and weapon system developments.

3. Retaining the Pilot

Many attempts have been made to find alternatives to the manned military aircraft - the past thirty years has seen the replacement of some types of manned military aircraft by unmanned alternatives - ballistic missiles, tactical guided weapons and ground based defences. Whether the military combat aircraft will ever be replaced is unclear. There is certainly no likelihood of this change in the near future. Carrying a man around, and protecting him against most eventualities puts constraints on the vehicle design. But the difficulties of delegating all the tasks he does and the decisions he makes to robotics and computers are currently insurmountable.

Of course, there are well supported programmes in the field of Artificial Intelligence, which lead to a better understanding of various aspects of human behaviour. There are many threads to these programmes - understanding decision processes, modelling of human sensors, software organisation to imitate human behaviour. The USAF Pilot Associate programme is a vigorous attempt to take advantage of, and to apply these ideas to the next generation of military aircraft. Aspects of the pilot's task are delegated to computers, which make decisions on whether information is available and advises the pilot on how to proceed. Some tasks will be completed automatically. But the pilot is not redundant - the programme objective is to help the pilot achieve a higher standard of performance.

There have been mixed opinions for seventy years on whether combat aircraft should have a one man or two man crew. Even now, although the new generation of fighters (EFA, Gripen, Lavi, Rafale) are all single seat, doubts still remain that one man can fly and manage all the systems in a fully effective way.

For all the capability which computers give to model operational scenarios, they are still deficient in representing the range of pilot activities. Certain thought processes of a simple kind, such as the choice of manoeuvre to achieve a position of advantage, can be programmed. Others cannot, particularly when conflicting demands arise, and when the information on which to base decisions is incomplete. Unfortunately, the majority of decisions which pilots are called on to make are in these categories.
The way ahead lies in manned simulation. Well established methods to develop flight control and other aircraft systems can be extended to examine operational scenarios in both air-to-air combat and air-to-ground combat attack.

4. Current Simulation Capabilities

Flight Simulators have contributed to aircraft design since the late 1950's. Initial successes were scored in the area of flying qualities and flight control. Handling criteria established in simulator tests were used as the basis for the development of current Flying Qualities Requirements. Consequently, flight control systems designed to meet these requirements received further evaluation on flight simulators.

More recently, much has been claimed for the combat performance improvement which can be derived from control-configured aircraft - by relaxing the requirement for natural stability and providing artificial stability through the control system. Since the safety of the aircraft is now dependent on flight control system integrity, more demands are placed on simulator and rig testing prior to flight. It is not an exaggeration to say that the flight control systems for new fighter aircraft could not be designed without the use of flight simulators.

Of even greater significance in the evaluation of combat aircraft performance has been the advent of Air Combat Simulation. The most successful air combat simulators employ domes, which contain a well-equipped cockpit, and display devices to project images of sky, ground and target aircraft onto the surface of the dome. Contributing to the success is the real-time modelling of the components of the scenario - aircraft, avionics, radar, missiles, displays and scoring. Table 1 lists some of the uses which are made of research air combat simulators.

Table 1

Air Combat Simulator Applications

Research and Development

Optimisation of aircraft configurations

Optimisation of missile configurations
Matching of airframe performance to missile performance

Evaluation of new concepts (VIFF, PST, fuselage arming)

Evaluation of weapon arming and sighting systems

Tactics in close combat and BVR combat

Tactics for engagement and disengagement

Evaluation of competitor and threat aircraft

Multi-combat

Operational factors - weather, ECM.

In its simplest form, the air combat simulator consists of a cockpit inside a single dome, onto which are projected images of the sky, and a target aircraft. The manoeuvres of this aircraft are controlled by the computer, which is programmed to imitate the tactics used in close combat. The tactics are dependent on the types of aircraft in combat, and on the weapons they carry. The computer controlled opponent is a valuable tool for preliminary assessment of aircraft and weapon configurations. The computer opponent provides consistent performance, is readily available and reduces experimental scatter. At the same time, questions arise concerning the validation of the computer model - should cockpit obscuration of view be modelled, and should random effects to represent pilot uncertainty or error be included? Also, to be modelled, the optimum tactics must be understood. With new configurations, the optimum tactics have still to be determined.

The twin-dome, one-versus-one air combat simulator overcomes these criticisms. Most of the twin dome air combat simulators in the USA and Europe also calculate and display the fly-out behaviour of missiles. The cockpits contain the fire-control systems for various weapon configurations; the modelling and cockpit displays embrace the radar and ECM environment to extend the simulation to Beyond Visual Range Combat.

Many lessons relating to aircraft and weapon system design can be learned from one-versus-one combat simulators. A need still exists to study the tactics and trade-offs in multiple aircraft combat. Once again the need to include the pilot in such studies is evident. Although 2 v 1 or even 2 v 2 tactics are amenable to analysis, successful co-operative tactics need skill and experience, with random factors, such as loss of sight of one opponent, playing a larger part than in the case of one v one combat.

Multi-aircraft engagements become a lottery, and strategies change. Most pilots would agree that energy becomes the critical factor, and that maintaining a high speed reduces the risk of being killed. It will, however, reduce the chance of a successful attack. Analytical studies of multi-aircraft engagements (m v n) regard a battle as won if one side has achieved a favourable kill ratio. Pilots do not see a mutual kill as having the same score as a mutual escape. Consequently, high attrition (even when the opponent attrition is greater) is not acceptable, and will change the tactics.

The provision of additional air target projectors inside a dome can now provide realistic simulation of multi-combat. The computing overhead of performance and relative geometry can be provided without undue cost. It is usual, however, to fly some of the competing aircraft from individual consoles, rather than provide each pilot with a fully equipped dome and display system.

5. Examples of Combat Simulator Trials

5.1 *Validation of a Computer Controlled Opponent (BACTAC)*

BACTAC is a computer programme developed by British Aerospace to replicate the tactics used by a pilot in close combat. It is used extensively, both for research work and in the pilot training courses which we regularly give to the Royal Air Force. The tactical rules it uses have evolved over several years of development in the nineteen seventies.

To engage the pilot, BACTAC continually re-assesses its view of the fight. It examines whether the piloted aircraft is:

ahead or behind,
pointing towards or away,
the range, and the range capability of the weapons.

From these decisions follow the choice of aggressive manoeuvres, defensive manoeuvres, or less extreme manoeuvres which include energy gain or conservation. Ground avoidance is another possible manoeuvre, and has priority over most other demands. The aggressive manoeuvres are sub-divided into regions of increasing threat to the opponent.

It is usual to justify the behaviour of programmes such as BACTAC by reference to pilot testimony. Controlled experiments to compare directly the success of a computer opponent with a pilot are rarely made (or rarely discussed). Four years ago, we conducted such an experiment funded by MoD (PE). Six RAF squadron pilots flew a large number of close-combat engagements, against either BACTAC or each other. The aircraft types were F5E and Phantom F4. Both aircraft were armed with rear-hemisphere IR missiles. Scoring measurements and pilot comments were recorded, together with all parameters needed to reconstruct each fight. Table 2 shows some of the measurements.

TABLE 2

	Average No. of shots		Average IAS knots		Average g	
F5 man v man	0.11	0.56	256	265	3.0	3.1
F5 man v BACTAC	0.39	0.11	255	244	3.3	3.0
F5 man v F4 man	1.06	0.06	382	491	2.7	2.9
F5 man v F4 BACTAC	5.39	0.00	295	435	3.4	4.7
F5 BACTAC v F4 man	1.17	0.00	291	402	2.7	3.3

In the case of the F5 v F5 fights, a good validation of BACTAC's logic was obtained. The scatter in the number of shots was less than in the man v man case. The speeds and the g levels are similar. Pilot opinion confirmed that BACTAC was fighting in a similar manner.

Validation of BACTAC is also seen in the scoring comparison of F5 v F4 fights, when BACTAC is flying the F5. The F5 has a better attainable turn rate than the F4, and has better sustainable turn rate at low speed. The only tactic open to the pilot of the F4 is to adopt high speed slashing attacks, to try to minimise the shot opportunities of the F5. Against this defence, BACTAC and the pilots showed similar tactics.

However, when BACTAC was given the F4 to fly against the F5, because it had been programmed to be aggressive rather than to minimise the shot opportunities, it lost heavily.

Other aspects which have been studied in this way include a comparison of escape manoeuvres against a computer controlled opponent. Such experiments provide a good insight into the programming of computer controlled opponents, and the changes needed to develop them for more complex scenarios, such as multiple combat.

5.2 Comparison of Advanced Combat Aircraft Configurations

The most general use of Air Combat Simulators in the Research context has been to compare the merits of aircraft/weapon configurations. New designs are compared with existing fighter aircraft (such as F16 and F18) and with postulated threat aircraft.

In making such comparisons, the type of plots seen on figures 1 and 2 are invaluable. They present the important parameters which influence success in air combat; by overlaying plots for different aircraft, the likely outcome of an engagement, and the tactics most likely to succeed, may be predicted.

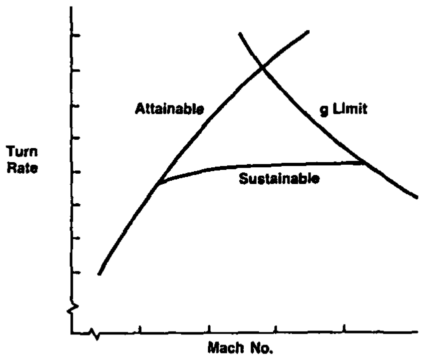


Figure 1

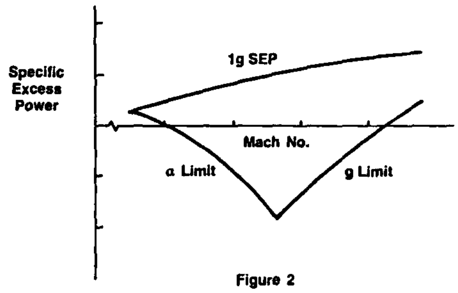


Figure 2

The plots do not tell the full story, however. Factors such as aircraft handling qualities (including care-free manoeuvring), cockpit design (visibility, seat comfort, switch operation), aircraft size and recognition of range can influence air combat success. Even more important are:

* the type of weapon carried by each participant

* the skill of the pilots in exploiting such advantage as they have.

It has been our experience that with improvements in performance of both aircraft and weapon, the difficulties of assessment in the Air Combat Simulator (or by any other process) have increased.

In studying the tactics for current fighters, armed with guns, and missiles of limited rear hemisphere capability, evaluations over many years have shown that sustained turn rate (STR) eventually wins the fight. If the performance advantage is not large, patience is needed, tactical mistakes are punished, but the lethality of the opponent is not so great and if the pilot sticks to a few simple rules, he will win, or keep out of trouble. Tricks like PST and VIFF are useful, as long as the energy lost in their deployment can be regained rapidly - implying the need for high thrust/weight ratio (high SEP).

If the aircraft performance is then improved to the level of the new range of combat aircraft, without improving the missile performance, the chances of a kill by an aircraft with an STR advantage of 2 - 3 degrees per second is much reduced. The slightly inferior aircraft can still turn inside the minimum range of the opponent's missile, and so deny him shots.

Introducing a high performance missile, with shorter minimum range and better off-boresight capability changes the nature of the fight. Turn rates are high, turn radii are small, and energy considerations do not inhibit the use of the vertical plane. In these fights, more pilot skill is needed to recognise firing opportunities, both outgoing and incoming. Split second timing is needed, and often a firing opportunity is only created by risking an exchange of shots. One consequence is that attainable turn rate is often used either to achieve or deny a firing opportunity, so that good ATR is at least as important as good STR.

The critical nature of the fight means that more care is needed in conducting trials on Air Combat Simulators. Pilots must be well briefed and familiar with the simulated aircraft and weapons systems, and sufficient data must be obtained to see a clear trend in the inevitable scatter.

5.3 Typical Trade-Off Studies

In spite of the reservations expressed in 5.2, the Air Combat Simulator remains the most effective way to evaluate the relative merits of combat aircraft/missile configurations. In any choice of aircraft characteristics to meet a given operational requirement, the sizing of the aircraft and engine is fundamental, and the Warton ACS has been used to determine the trade-off between thrust and wing area in support of such decisions at the conceptual stages of proposed projects.

As an illustration, Figure 3 defines seven test configurations selected for comparison in the ACS. Assuming a constant weight, engine thrust and wing area were varied. Increased engine thrust improves SEP, and sustained turn rate to a small extent, leaving ATR unchanged. Increased wing area improves both STR and ATR, leaving SEP unchanged.

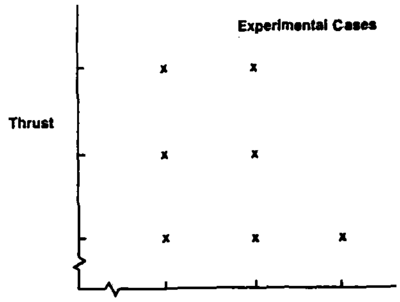


Figure 3

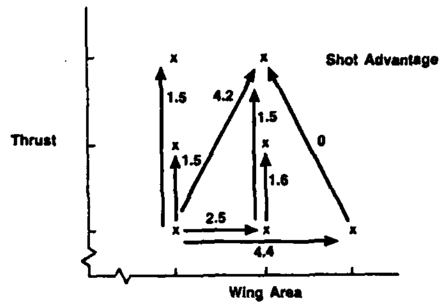


Figure 4

A large number of 1 v 1 combat engagements were flown to compare the seven configurations, all armed with the same short-range IR missile. Figure 4 shows the relative shot advantage of one configuration compared to another. The best and the worst configurations were also flown against a current fighter and a postulated threat. From these results a 'minimum acceptable' close-combat line could be constructed (figure 5). Other considerations, from independent studies (by the Royal Aircraft Establishment at Farnborough, U.K.) also produced a 'minimum acceptable' BVR line. Such graphs form a useful briefing aid to Air Staff and other officials.

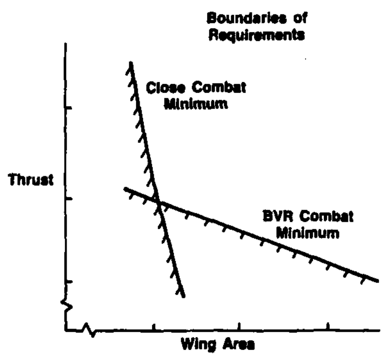


Figure 5

5.4 Operational Tactics

The basis for success in combat lies in superior equipment, and superior numbers. Not only can simulator studies contribute to the choice of the best aircraft and weapon configuration, it can then evaluate the best tactical use of the chosen configurations.
Perhaps the simplest example is the use of the 1 v 1 twin dome ACS to study the techniques for disengagement from combat. Limits imposed by fuel use or expended weapons are easily

simulated, and pilots can try repeatedly the techniques required to leave the fight. Against a superior opponent, difficulties arise, since the whole basis for escape lies in achieving sufficient energy to 'run-out' without undue exposure to a shot. Energy gain comes either from the loss of positional advantage or from height. Also critical in escape manoeuvres is a knowledge of the capability of the opponent's weapon against a receding target.

Tactics become more complex in multiple-combat. The large dog-fights of WW2 may never be repeated. From all accounts, the greatest danger was that of being hit by an opponent of which you were unaware. Although the fighters were only armed with fixed guns, attrition was high.

It is hard to image the scenario if many modern aircraft armed with advanced short range missiles were to engage. From the pilot's point of view, he has to control a more complex aircraft, a more complex weapon system, and he is more vulnerable because of the high P_k and large release boundaries of his opponent's weapons. Adding to the confusion is the difficulty of ensuring that weapons are in fact released against an opponent rather than a colleague, or that the weapon does not reacquire after release onto an unsuspecting party. A further consideration is the head-on kill capability which the next generation of short range missiles will have. Unless counter-measures effective against the head-on attack are found, the safest tactic is to keep outside the melee, and use high speed slashing attacks. It is then difficult to see how the dog-fight will develop in the first place.

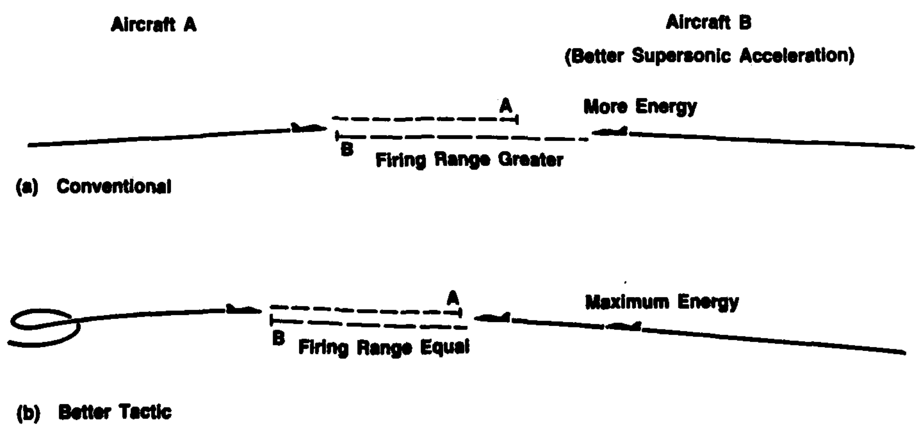
A more likely scenario for the next generation of fighter is Beyond Visual Range Combat (BVR). Although mathematical modelling will give some insight into the tactics which may succeed, the case for manned simulation is even stronger than that for close combat assessments. The decision process imposed on pilots is more complex. Their information about their opponents is of poor quality. The radar returns may be subject to interference, and the displayed information, when processed, needs interpretation. The flight time of both the incoming and outgoing missiles is long, so that counter-measures, in the form of manoeuvres to break lock, can be successful.

Even the simplest case of one v one BVR combat requires a high degree of sophistication in the simulator to allow representative assessments to be made. The modelling of radar and missile fly-out must be accurate, together with a simulation of each aircraft which reflects the workload and performance in subsonic and supersonic flight.

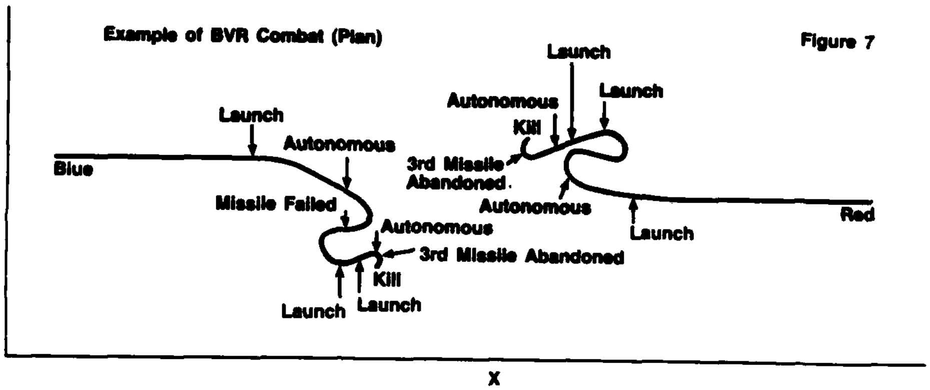
Our experience in simulating one v one BVR combat has demonstrated that pilots will adopt unusual tactics in order to win - tactics which would probably not emerge from a mathematical model of the situation. The typical BVR scenario assumes large separation (80km) on target acquisition, and assumes that the weapon is initially relying on guidance from the launch aircraft, and then locks onto the target. Once the missile is autonomous, the launch aircraft can look after itself, and the aircraft under attack becomes aware that it is in imminent danger.

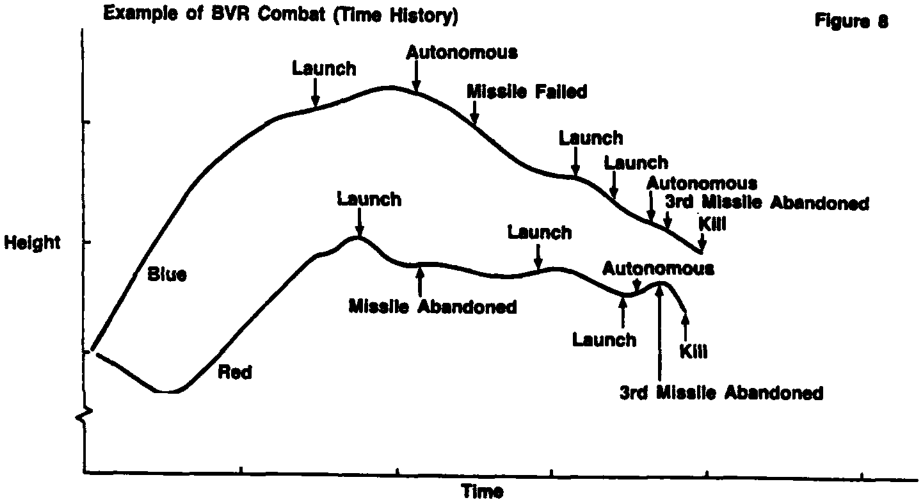
Good SEP and supersonic turning performance is needed for attack and evasion in BVR. One tactic seen in our experiments negated the SEP advantage. From a neutral starting point (co-speed, co-altitude) rather than accelerate towards his opponent, the inferior aircraft turned away from the fight, and so gained time to accelerate, outside the range of his opponent. At the appropriate time he re-enters the fight, on equal terms with respect of energy (Figure 6).

One v. One BVR Strategy **Figure 6**



The other device that pilots enjoyed using was to fire a missile outside its maximum range. Although it had no chance of success, the opponent was not aware of this, and in taking avoiding action, was more vulnerable to a second shot. Typical time-histories of a BVR engagement terminating in mutual kills, are seen on figures 7 and 8.





6.0 Future Prospects

The value of using ground based simulators for evaluating performance improvements is now widely recognised. Currently, however, the improvements from different sources are studied separately. As we have seen, airframe or weapon system improvements are studied in air combat simulators. Improved cockpit layout, or better avionic fit, to give improved performance, is evaluated on avionic rigs. Multi-aircraft air combat has been represented by combining dome simulators with computer controlled opponents, and with opponents controlled from consoles with graphic displays. Multi-aircraft tactics have also been studied on instrumented Combat Manoeuvring Ranges.

Considerable investment is being made in Europe and the USA to improve research simulator facilities, both in Industry and in Government Establishements. Advances have been made in the technology of simulation, particularly in the field of visual displays. The most expensive systems offer great capability to produce complex images of the ground, of airborne targets, of missiles in flight, and of weather. High resolution images and a wide field of view are also on offer.

Consequently, the ability to simulate complete sorties, with representative combat scenarios, is appearing. Air-to-air combat at low level will soon be simulated realistically, both for helicopters and for fixed wing aircraft. Low level operation may emphasise the need to provide better motion cues, particularly if a representative pilot workload is regarded as important.

With this capability, the potential for full operational simulation is available. The computing requirement is considerable, but is not a limiting factor. Perhaps the structure and organisation of such simulations will test our ingenuity. Engineering Simulation has always been regarded as a meeting point for design disciplines. Full mission simulation, with many participants, greatly extends the invitation list.

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These proceedings contain the unclassified papers presented at the AGARD Flight Mechanics Panel Symposium on "The Improvement of Combat Performance for Existing and Future Aircraft", held in Treviso, Italy from 14 to 18 April 1986.

In planning the enhancement of a defence capability to meet a growing threat within increasing financial constraints, it is invariably necessary, and is current practice in all NATO countries, to consider varying options for improvement of existing weapon systems as an alternative to embarking on totally new systems concepts. A wide range of technical options are now available to improve the overall performance of a weapon system. Many of these features are equally applicable for embodiment in new designs or in existing combat aircraft. In considering these varied options, cost and effectiveness remain the common constraints.

The intention of this AGARD multi-panel symposium was to present the audience with examples of typical requirements for these types of programmes and to give overviews of the most relevant technical disciplines, showing the highlights of the most promising future trends and to comment on examples of realised or planned programmes. Though the technical scope of the symposium was very broad with active contribution from six AGARD Panels (FMP, FDP, SMP, PEP, GCP, AVP), clear statements and trends were projected in the individual presentations, discussions and in the final Round Table summary.

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